Institute of Paper Science and Technology

SLIDE MATERIAL

To The

PAPERMAKING

PROJECT ADVISORY COMMITTEE

April 27, 1993

Atlanta, Georgia

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Institute of Paper Science and Technology
Atlanta, Georgia

PAPERMAKING

FUNDAMENTALS OF THIN-FILM LIQUID COATING

PROJECT 3674

April 27, 1993
Institute of Paper Science and Technology
Atlanta, Georgia

PROGRESS REPORT

TO THE

PROJECT ADVISORY COMMITTEE

ON

PROJECT 3674

FUNDAMENTALS
OF
THIN-FILM LIQUID COATING

By

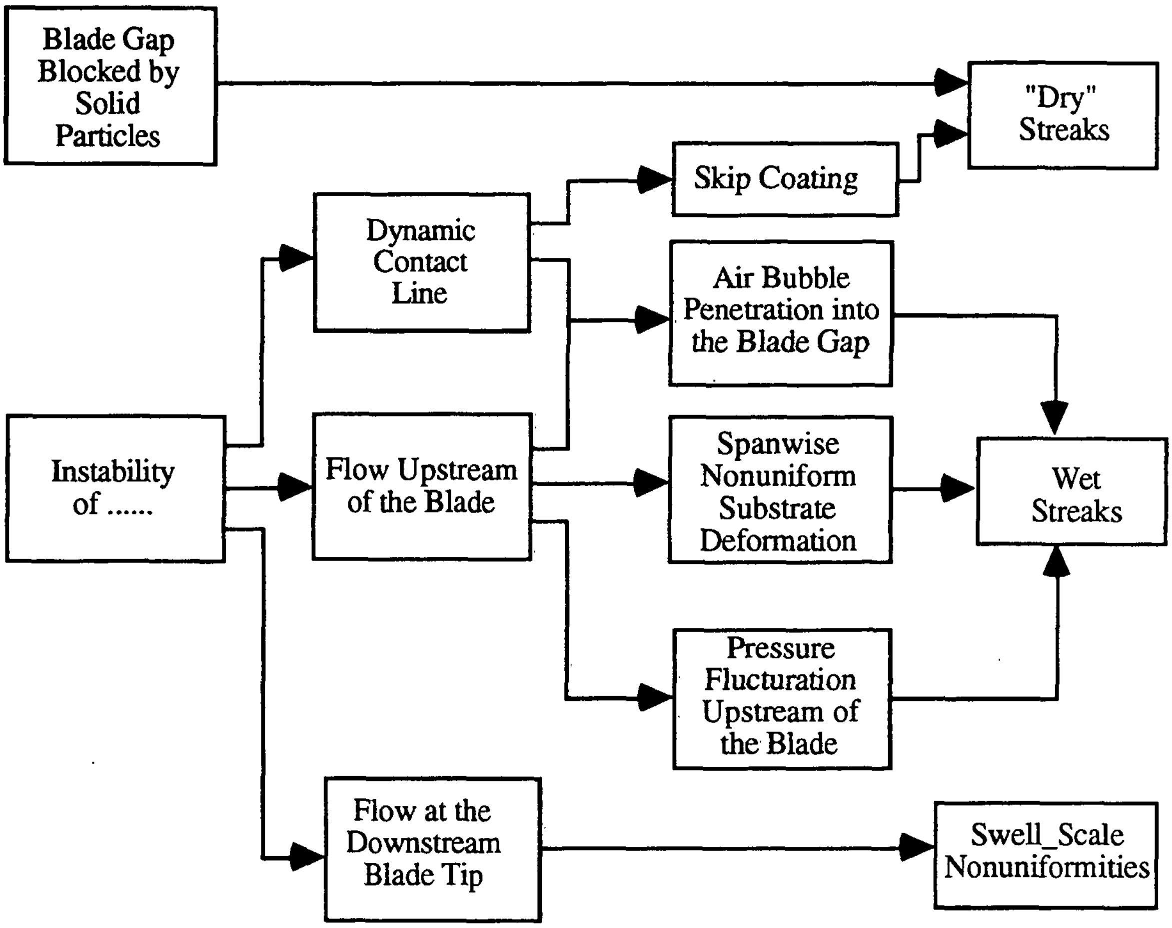
Cyrus K. Aidun
Associate Professor of Engineering

Institute Of Paper Science And Technology
A privately funded nonprofit graduate university

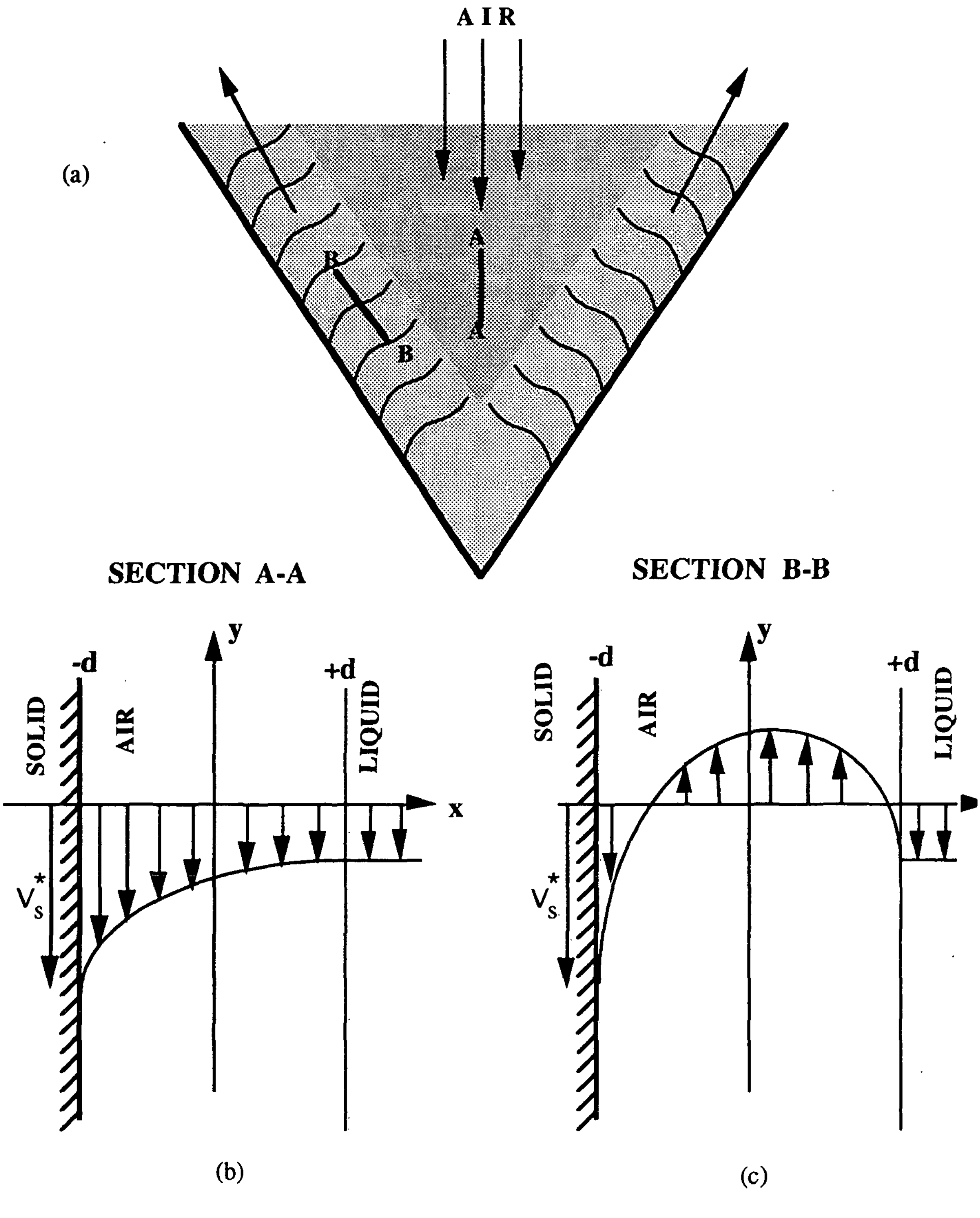
ORGANIZATION OF THE PRESENTATION

1. SOME BACKGROUND INFORMATION
2. REVIEW OF THE RESULTS
3. RECENT DEVELOPMENT IN THE COATING PROJECT
4. SHORT-TERM RESEARCH PLANS
5. UPDATE OF THE NSF/NYI PROJECT

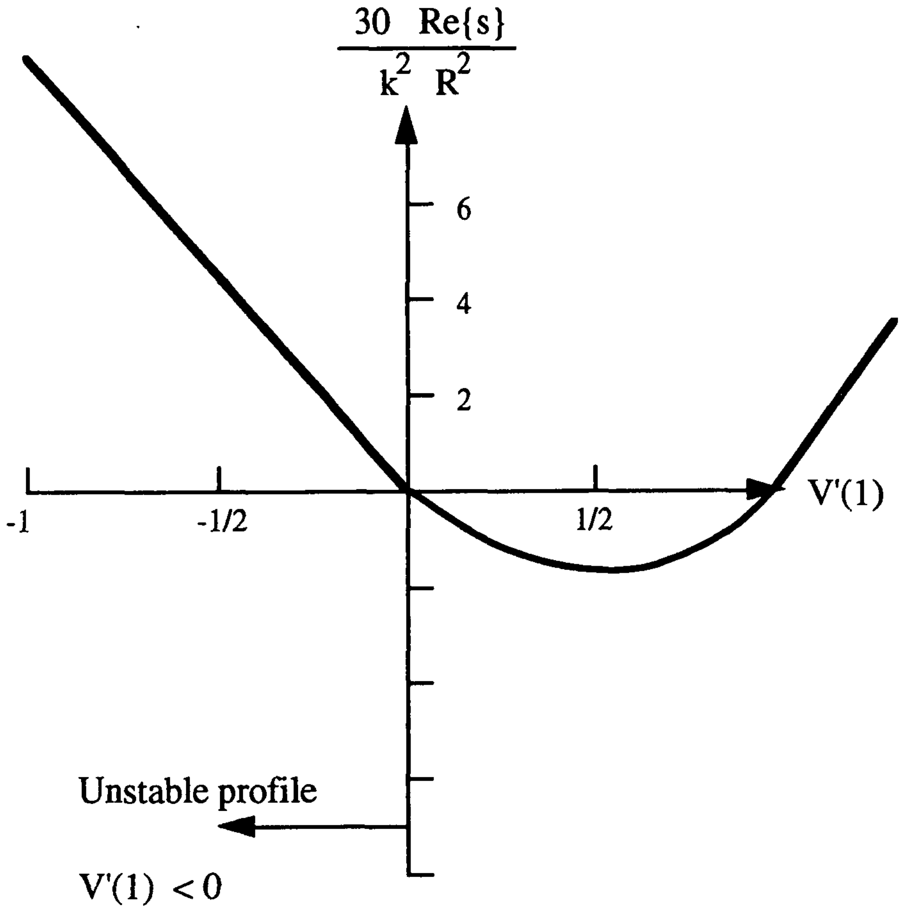
COATING DEFECT MECHANISMS



AIR ENTRAINMENT MECHANISM IN COATING



STABILITY ANALYSIS OF AN AIR/LIQUID INTERFACE



Growth rate, $\mathrm{Re}\{s\} = \frac{R^2}{30}\left\{4\left[\frac{1}{2} - V'(1)\right]^2 - 1\right\}k^2 + O(k^3)$

Phase speed, $\phi = -\,\mathrm{Im}\{s\}/k = (k-1)R\,V'(1) + O(k^2)$, $k \ll 1$

STABILITY ANALYSIS OF AN AIR/LIQUID INTERFACE

The stability analysis of an air/liquid interface assuming Newtonian liquid shows:

(1) Increasing the shear viscosity of the liquid enhances interfacial instability and consequently air entrainment

(2) The phase speed of the waves at the interface agree with experimental observations

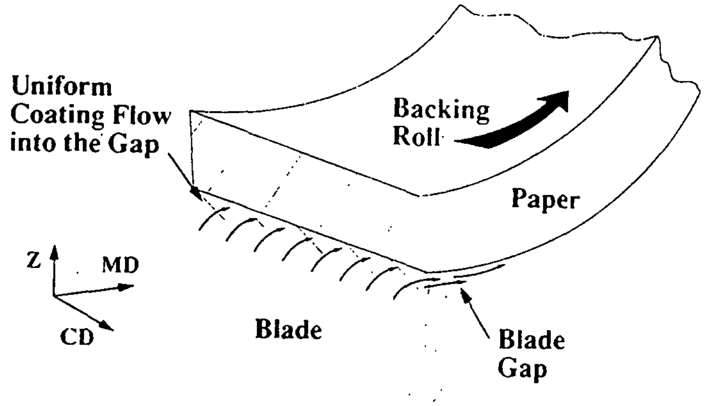


Figure 6.

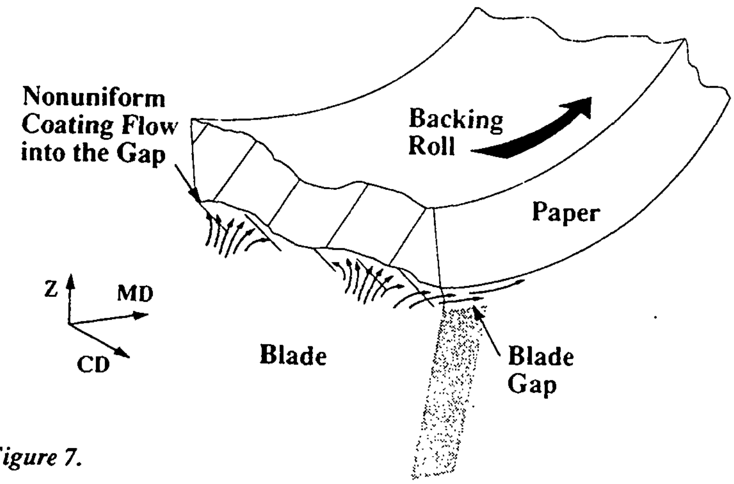


Figure 7.

Short-Term Research Plans

1. Dynamic Contact Line

   A fundamental study of the interaction of the coating fluid coming into contact with a moving surface at velocities of up to 2000 m/min. The extensional stress levels experienced by the coating fluid in the neighborhood of the dynamic contact line.

2. Air Entrainment

   Mechanism of air entrainment at high-speed

   Effects of air entrainment on surface properties

   How would the rheological characteristics of the fluid influence air entrainment into the system from the contact line.

3. Rheological Characterization

   Identify the key rheological characteristics of coating colors which can explain the problem with runnability of certain formulations.

   Devise a model or theory that can provide a prediction of the rheological data to coater performance.

   Establish a consistent rheological constitutive model for use in computational analysis and optimization.

	U_p	L_{in}	L_{gap}	$q = 2U_pL_{in}/3$	U_w	surf.tens	μ_∞ viscosity	μ_o viscosity	K	ρ density	n	COM-MENTS
Run	m/s	m	m	l/s/m	m/s	kg/s^2	kg/(m s)	kg/(m s)		kg/m^3		
C1	3.0	0.0025	$50\ 10^{-6}$	5.00	20.0	0.05	0.05	1.00	0.01	1200	0.65	<-- S
C2					30.0							S
C3					40.0							S
C11	5.0	0.0025	$50\ 10^{-6}$	8.33	20.0	0.05	0.05	1.00	0.01	1200	0.65	S
C12	8.0			13.33								S
C13	12.0			20.0								S
C14	16.0			26.67								A
C15	20.0			33.33								<-- A

INPUT PARAMETERS FOR THE SIMULATION OF NON-NEWTONIAN FLOW (Carreau Model)

TABLE 1.

A, Attached Flow
S, Separated Flow

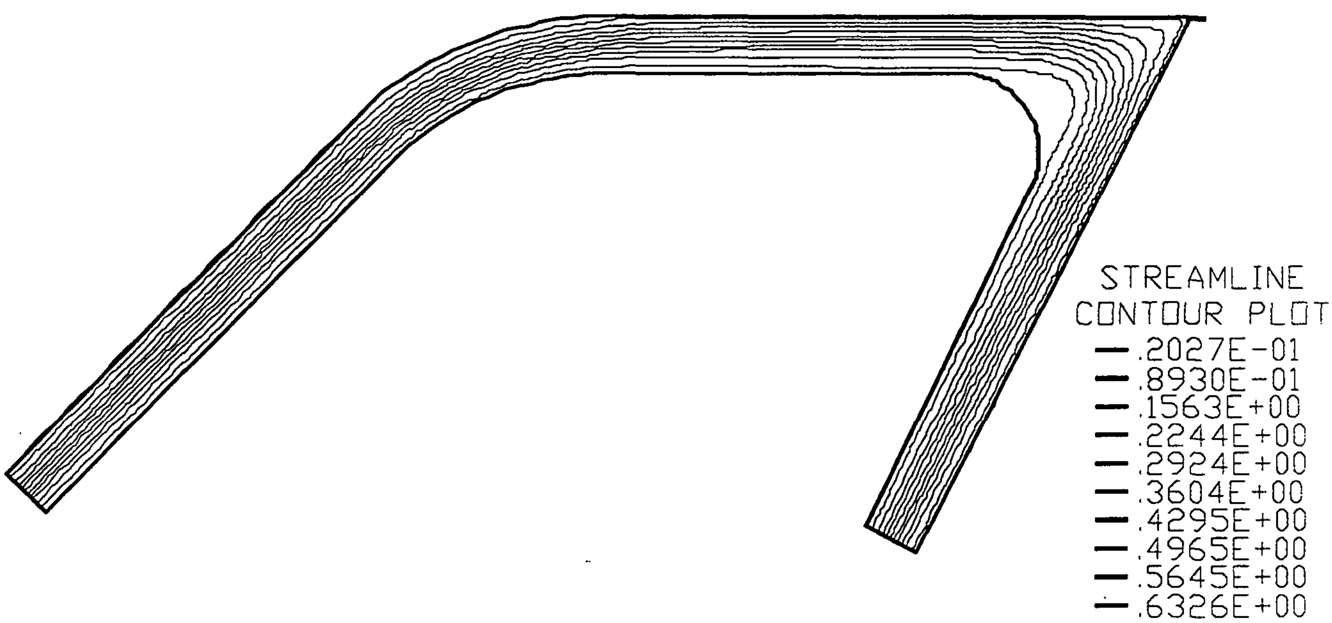
	U_b	L_{in}	L_{gap}	q pumped	q	U_w	surf.tens	μ_x viscosity	μ_o viscosity	K	ρ density	n	COM-MENTS
Run	m/s	m	m	l/s/m	l/s/m	m/s	kg/s^2	kg/(m s)	kg/(m s)		kg/m^3		
NB51	5.0	0.0025	$50\ 10^{-6}$	0.0	6.25	30.0	0.05	0.05	1.00	0.01	1200	0.65	S
NB52	5.0			2.5	8.75								S
NB53	5.0			5.0	11.25								S
NB54	10.0			0.0	12.50								S
NB55	10.0			5.0	17.50								<-- A
NB61	5.0	0.0025	$50\ 10^{-6}$	5.0	11.25	40.0	0.05	0.05	1.00	0.01	1200	0.65	S
NB62	10.0			5.0	17.50								A
NB63	15.0			5.0	23.75								A

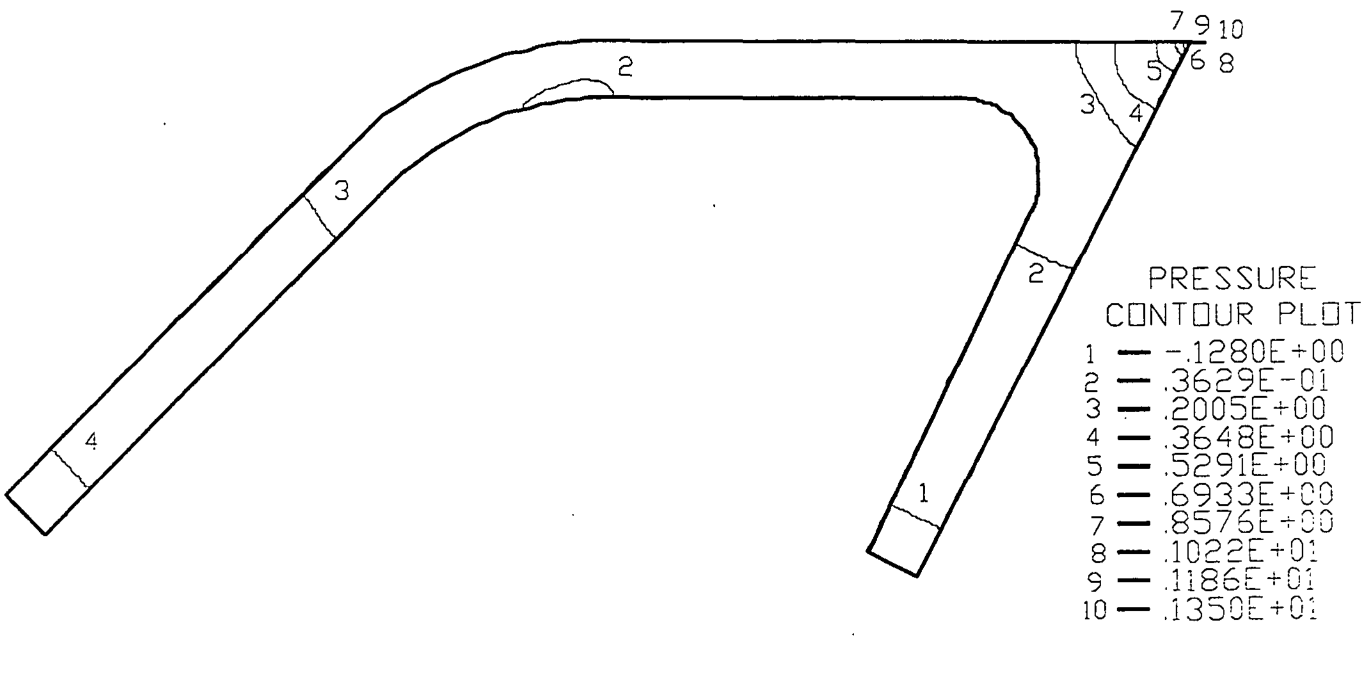
INPUT PARAMETERS FOR THE SIMULATION OF NON-NEWTONIAN FLOW (Carreau Model)

TABLE 2.

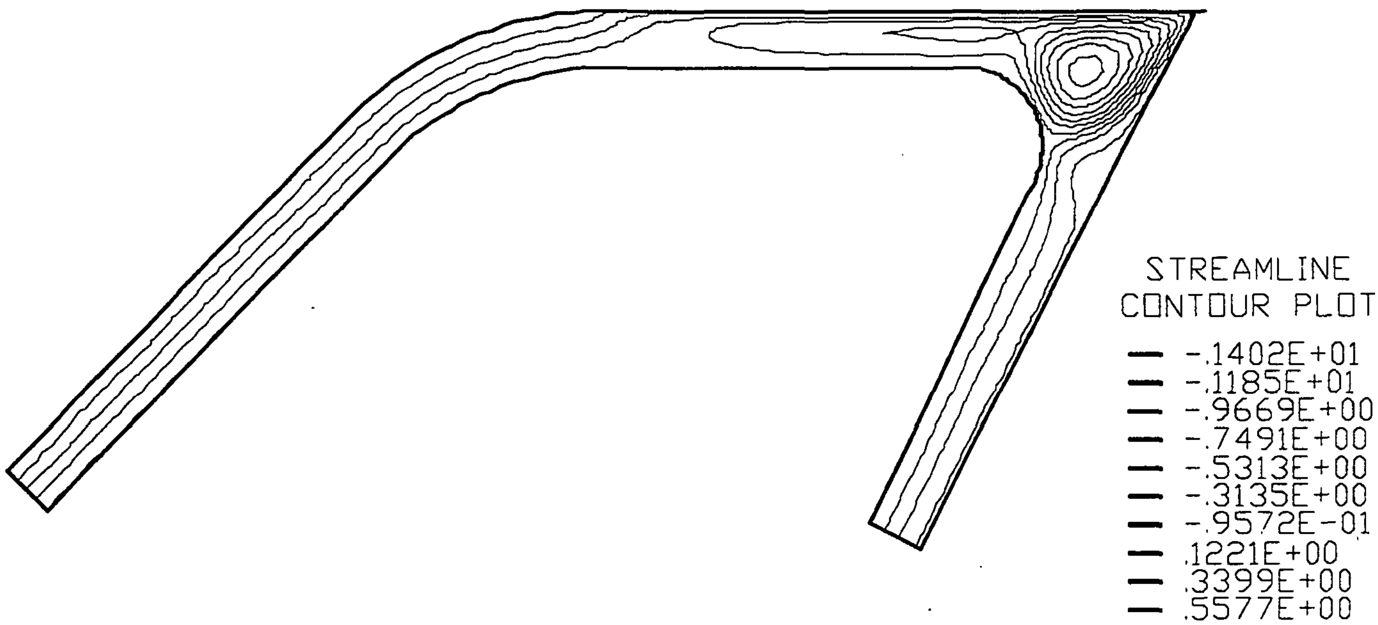
A, Attached Flow
S, Separated Flow

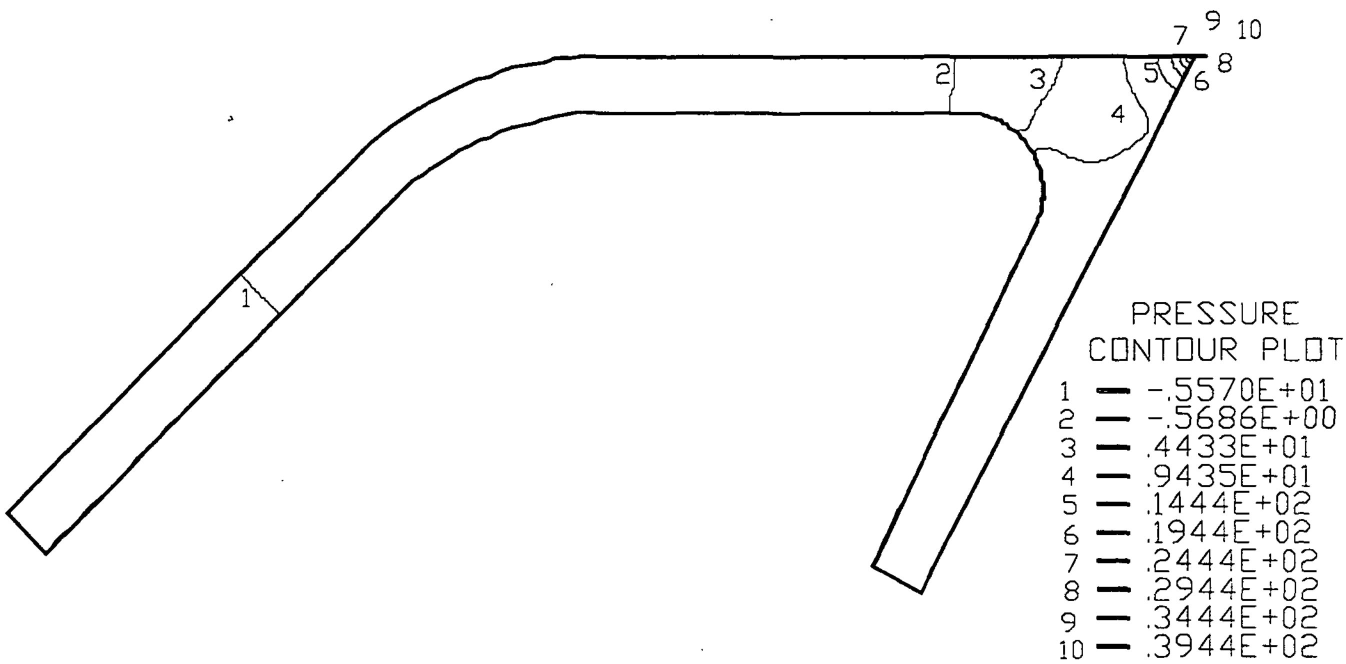
C15


STREAMLINE
CONTOUR PLOT
.2027E-01
.8930E-01
.1563E+00
.2244E+00
.2924E+00
.3604E+00
.4295E+00
.4965E+00
.5645E+00
.6326E+00

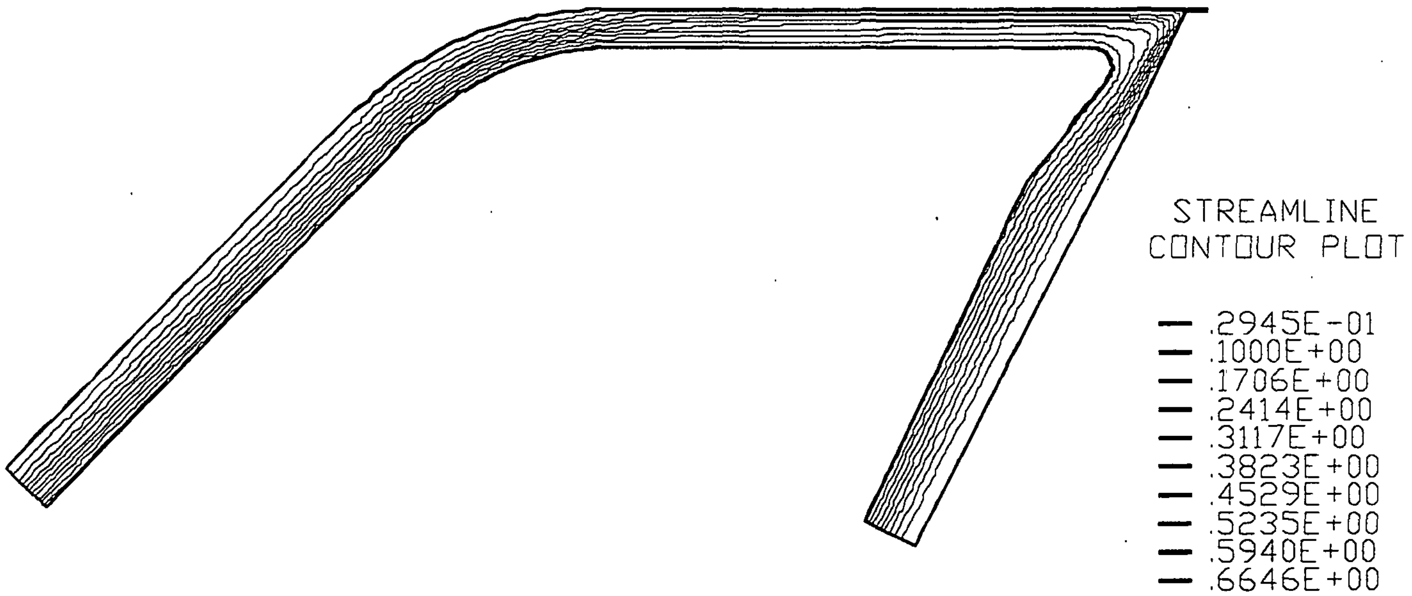

PRESSURE
CONTOUR PLOT
1 — -.1280E+00
2 — .3629E-01
3 — .2005E+00
4 — .3648E+00
5 — .5291E+00
6 — .6933E+00
7 — .8576E+00
8 — .1022E+01
9 — .1186E+01
10 — .1350E+01

C1

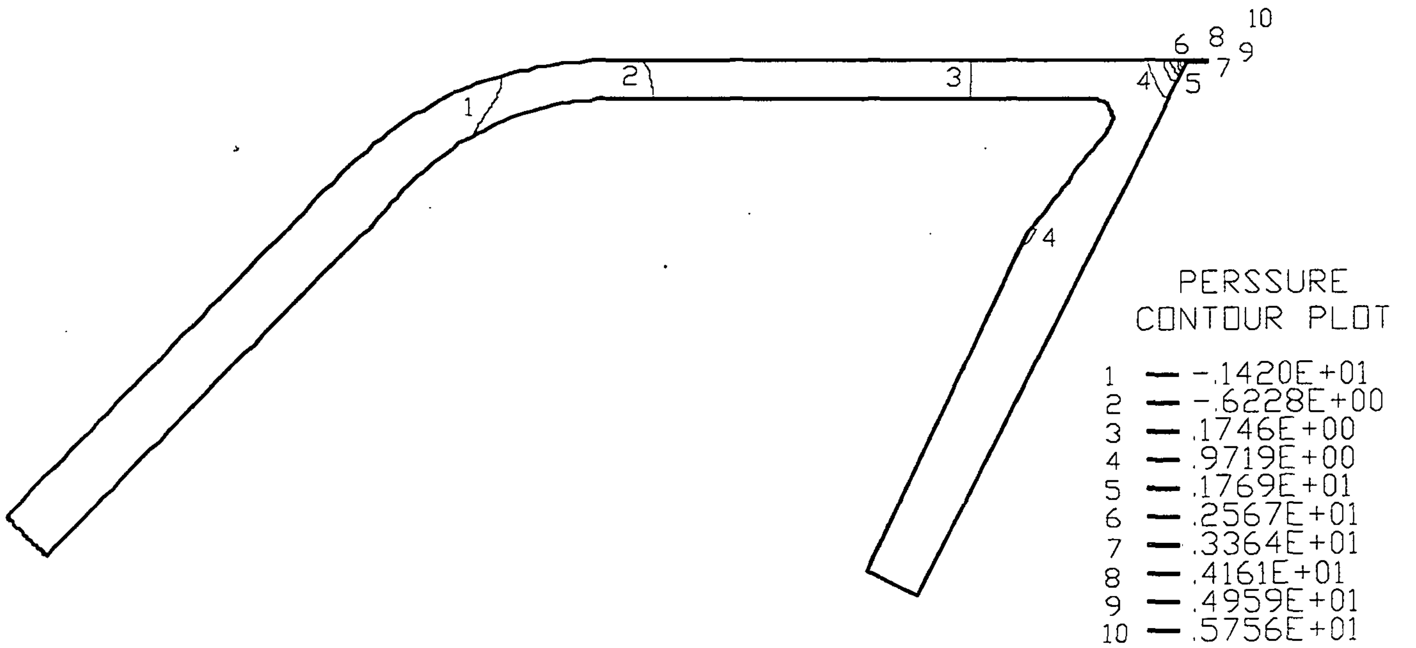

STREAMLINE
CONTOUR PLOT
-.1402E+01
-.1185E+01
-.9669E+00
-.7491E+00
-.5313E+00
-.3135E+00
-.9572E-01
.1221E+00
.3399E+00
.5577E+00


7 9 10
8
2
3
5
6
4
1
PRESSURE
CONTOUR PLOT
1 -.5570E+01
2 -.5686E+00
3 .4433E+01
4 .9435E+01
5 .1444E+02
6 .1944E+02
7 .2444E+02
8 .2944E+02
9 .3444E+02
10 .3944E+02

NB55



STREAMLINE
CONTOUR PLOT
.2945E-01
.1000E+00
.1706E+00
.2414E+00
.3117E+00
.3823E+00
.4529E+00
.5235E+00
.5940E+00
.6646E+00



1
2
3
4
5
6
7
8
9
10
PERSSURE
CONTOUR PLOT
1 -.1420E+01
2 -.6228E+00
3 .1746E+00
4 .9719E+00
5 .1769E+01
6 .2567E+01
7 .3364E+01
8 .4161E+01
9 .4959E+01
10 .5756E+01

LONG-TERM OBJECTIVES

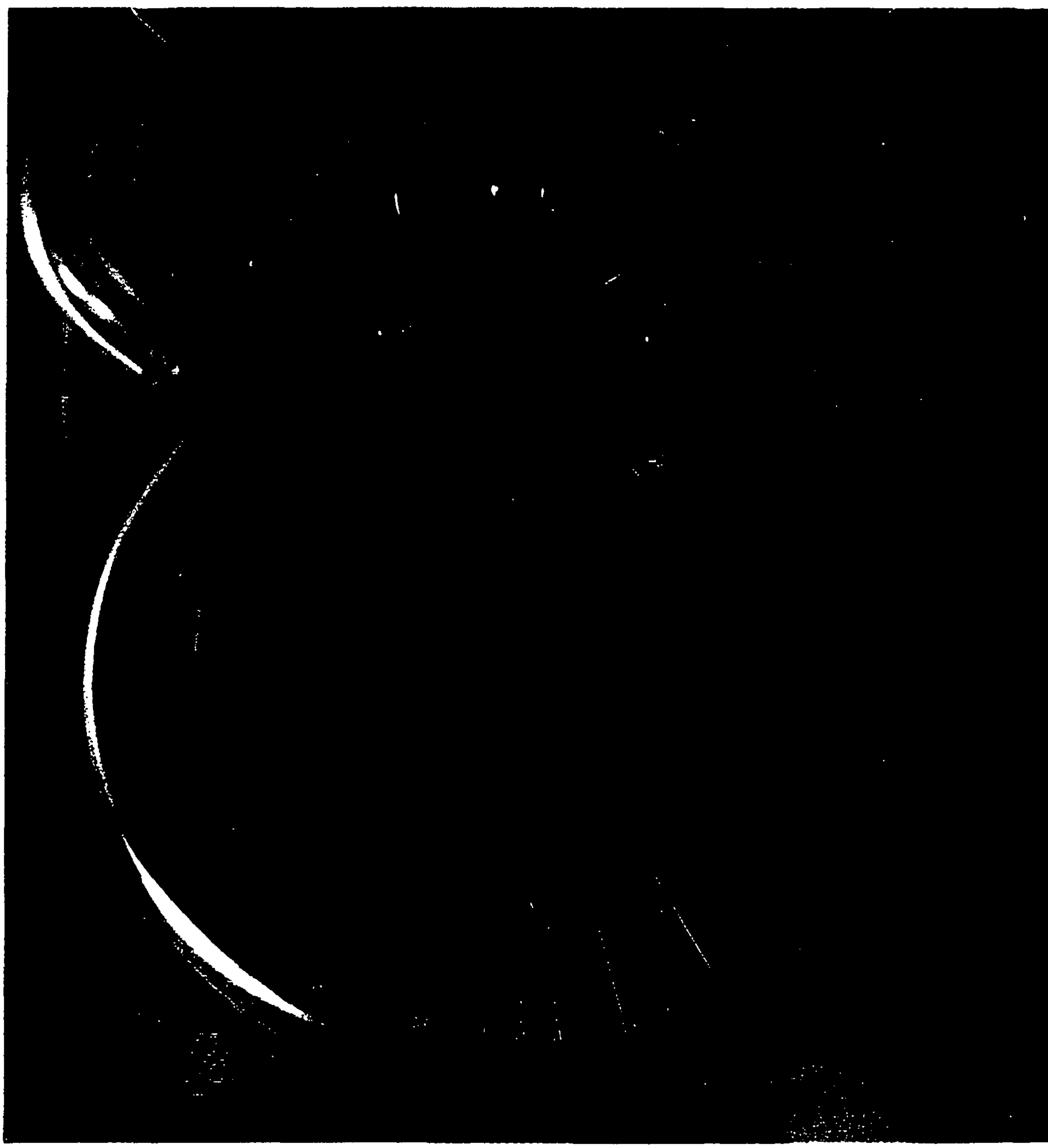
1. Develop a new high-speed coating system to provide acceptable coat-weight uniformities in both <u>macroscopic</u> and <u>microscopic</u> scales at machine speeds up to 2400 m/min with a <u>broad spectrum of coating formulations</u>.

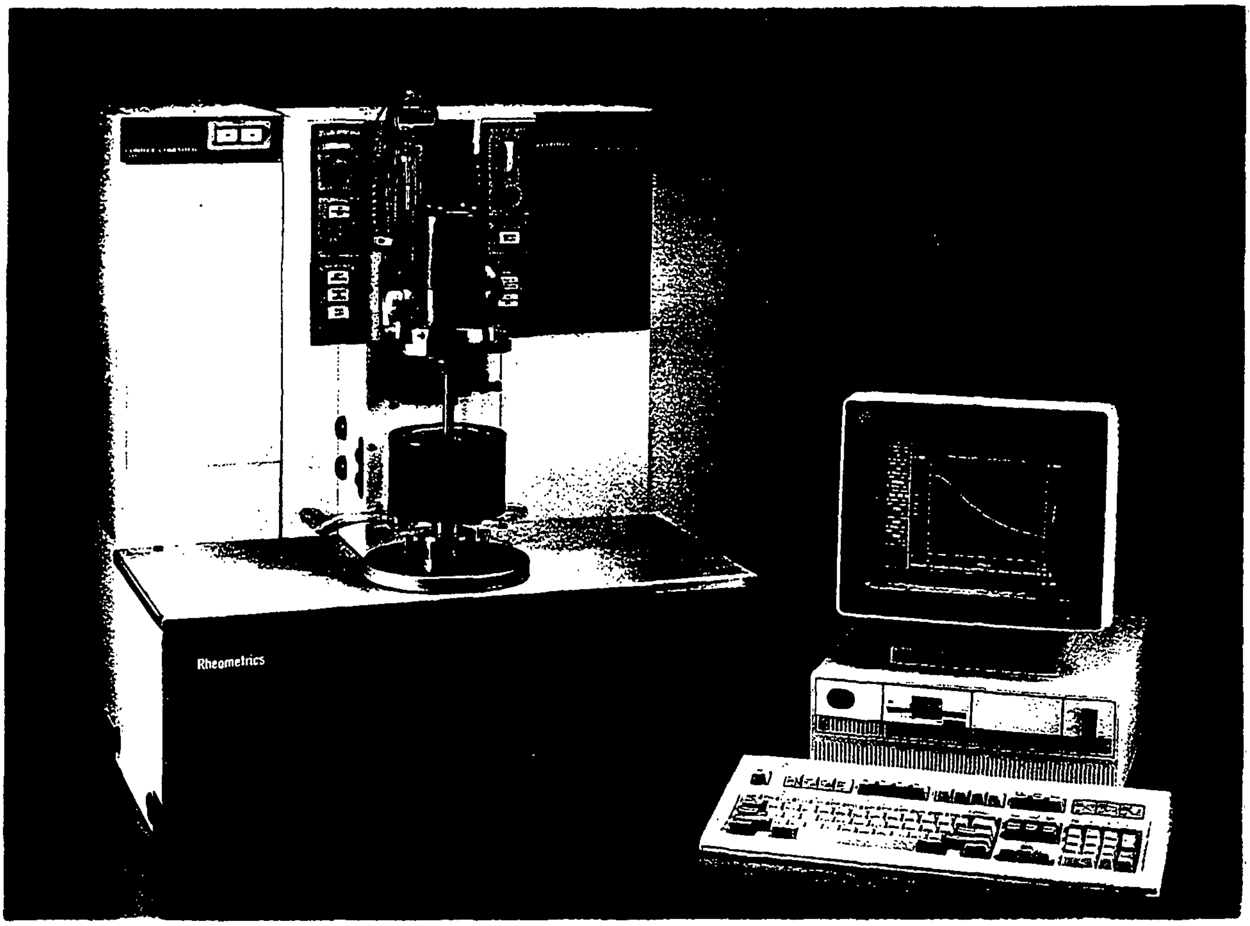
2. Assist in the development of an improved short-dwell coater to allow a wide operating window in terms of coating formulations.

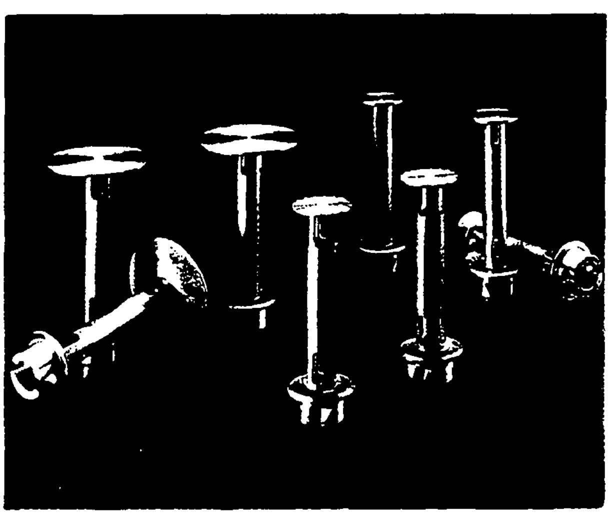
3. Develop on-line instrumentation for <u>rheological characterization</u> and <u>control</u> of coating colors.

Rheometrics

Fluids Spectrometer RFS II

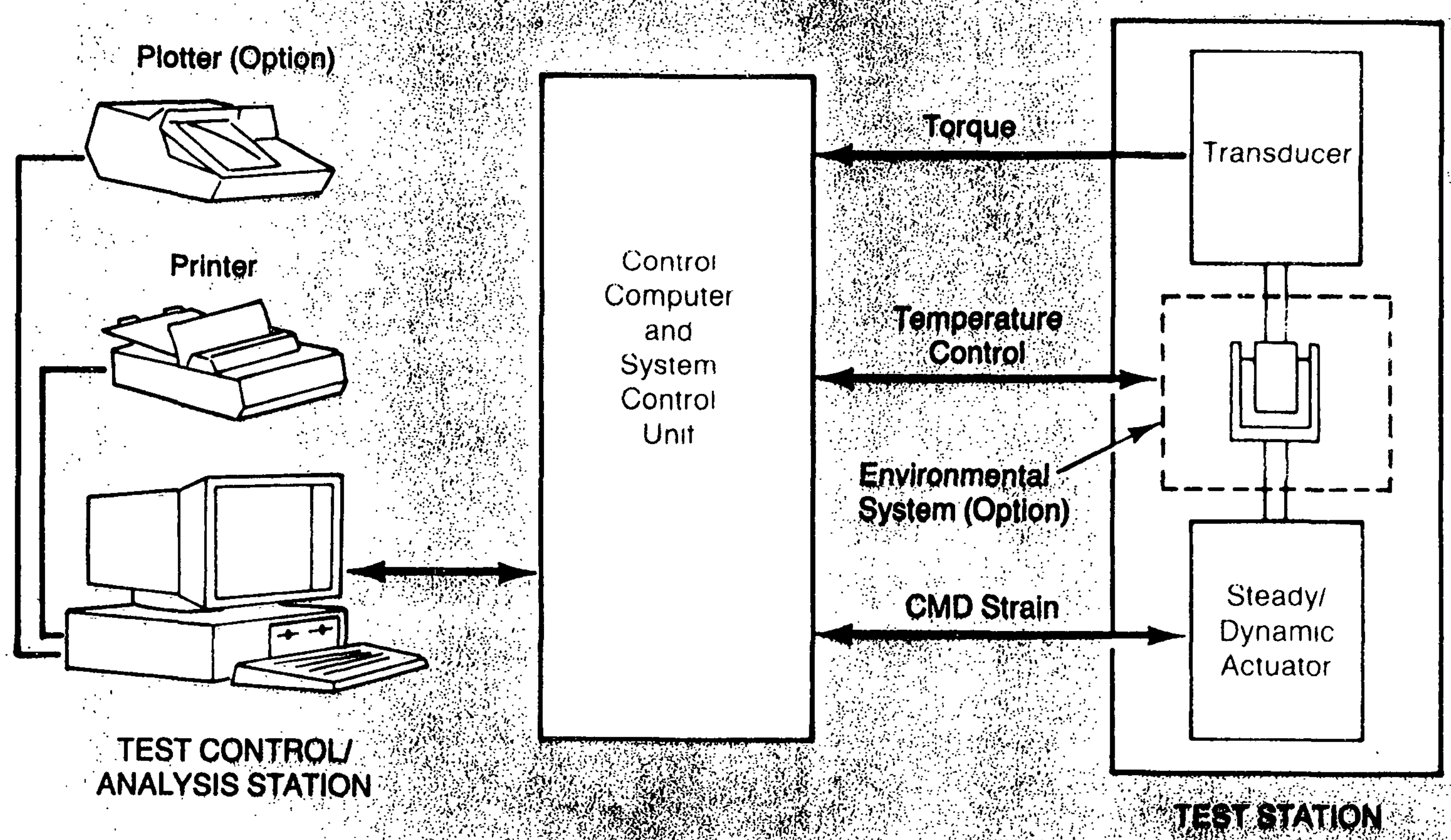






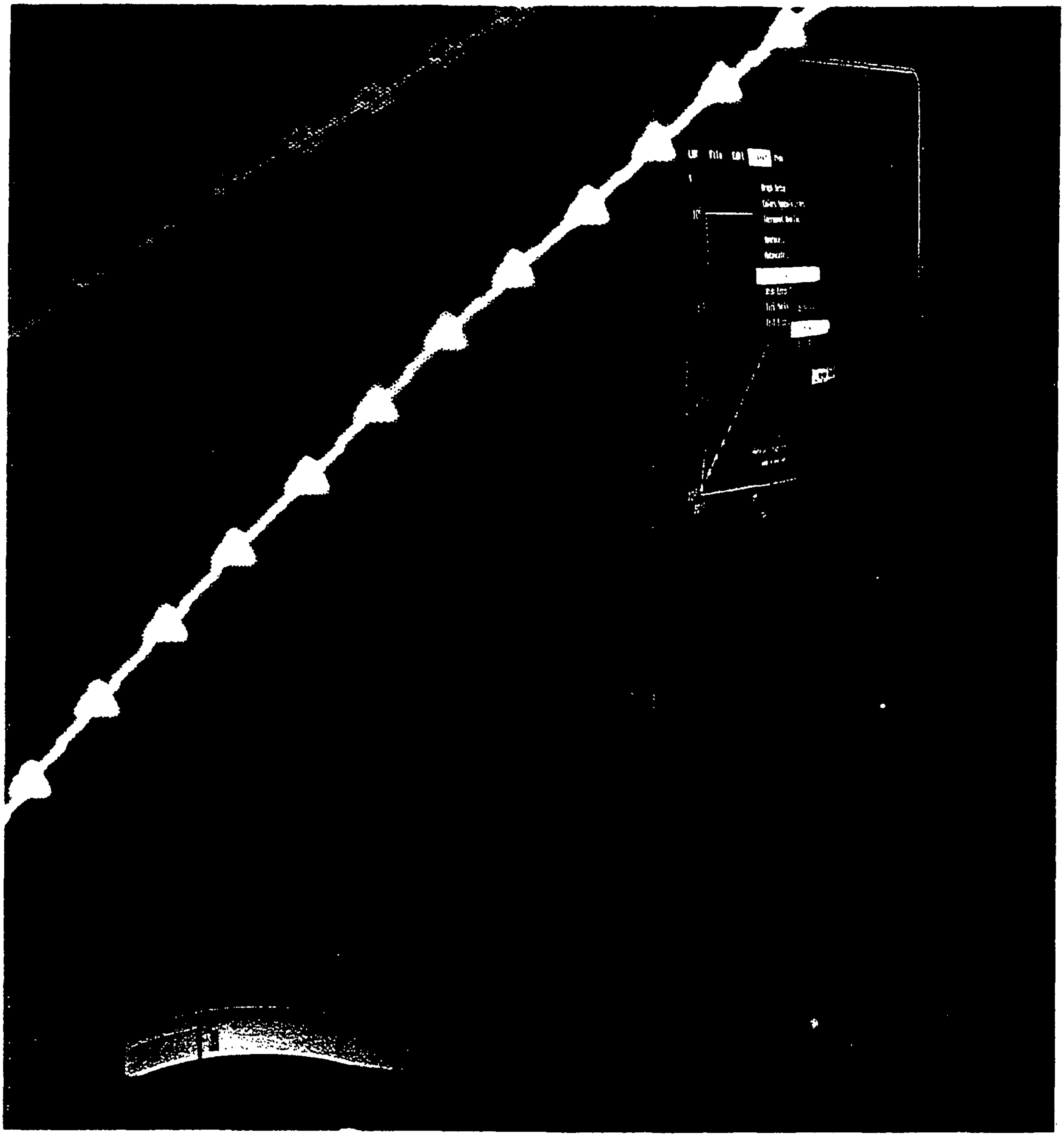
A variety of test geometries are available including parallel plates, cones, and serrated plates (pictured here), as well as couettes and coni cylinders in several sizes

A quick-connect tool mounting system allows fast, easy tool changes with assured tool parallelism and concentricity


Plotter (Option)
Printer
TEST CONTROL/
ANALYSIS STATION
Control
Computer
and
System
Control
Unit
Torque
Temperature
Control
Environmental
System (Option)
CMD Strain
Transducer
Steady/
Dynamic
Actuator
TEST STATION

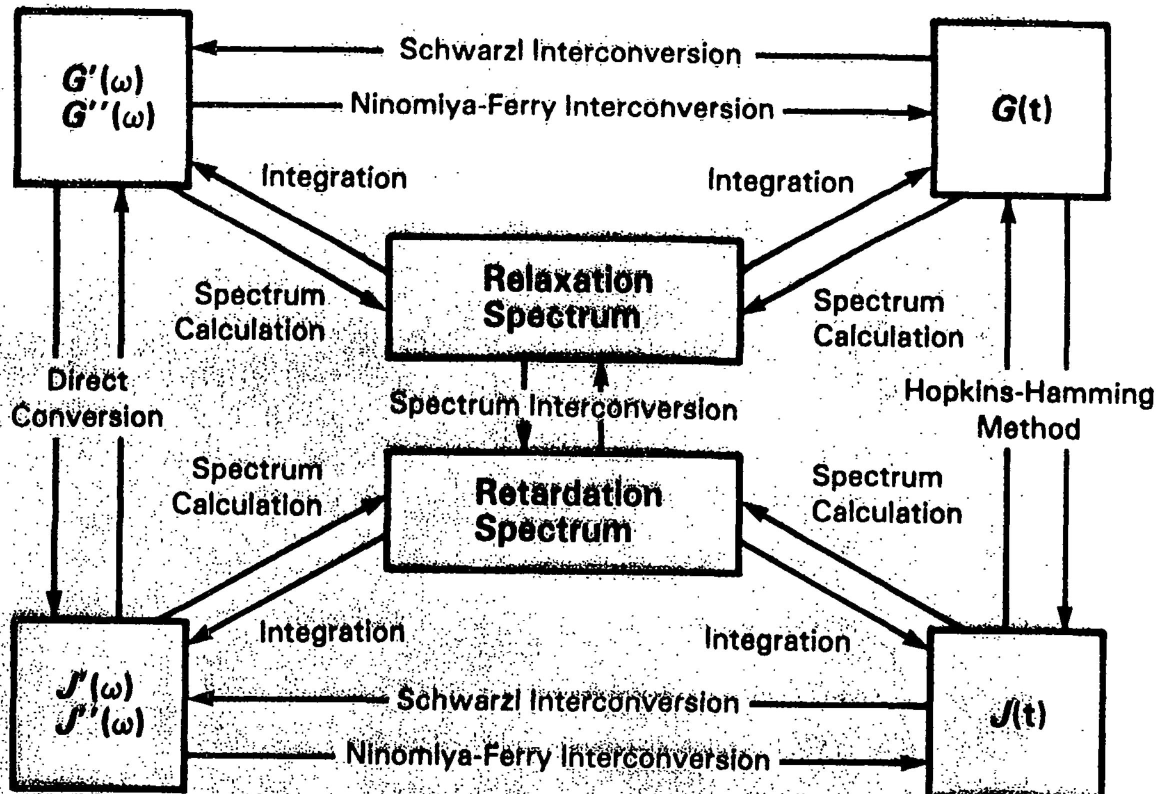
Rheometrics

RHIOS/RHECALC Rheometer Software



Rheological Transformations

The various transformations and pathways between dynamic and transient data and relaxation and retardation spectra, and the methods used to accomplish them.



PAPERMAKING

FUNDAMENTALS OF AIR/SHEET INTERACTIONS

PROJECT 3730

April 27, 1993
Institute of Paper Science and Technology
Atlanta, Georgia

PROGRESS REPORT

TO THE

PROJECT ADVISORY COMMITTEE

ON

PROJECT 3730

FUNDAMENTALS
OF
AIR/SHEET INTERACTIONS

By

Cyrus K. Aidun
Associate Professor of Engineering

Institute Of Paper Science And Technology

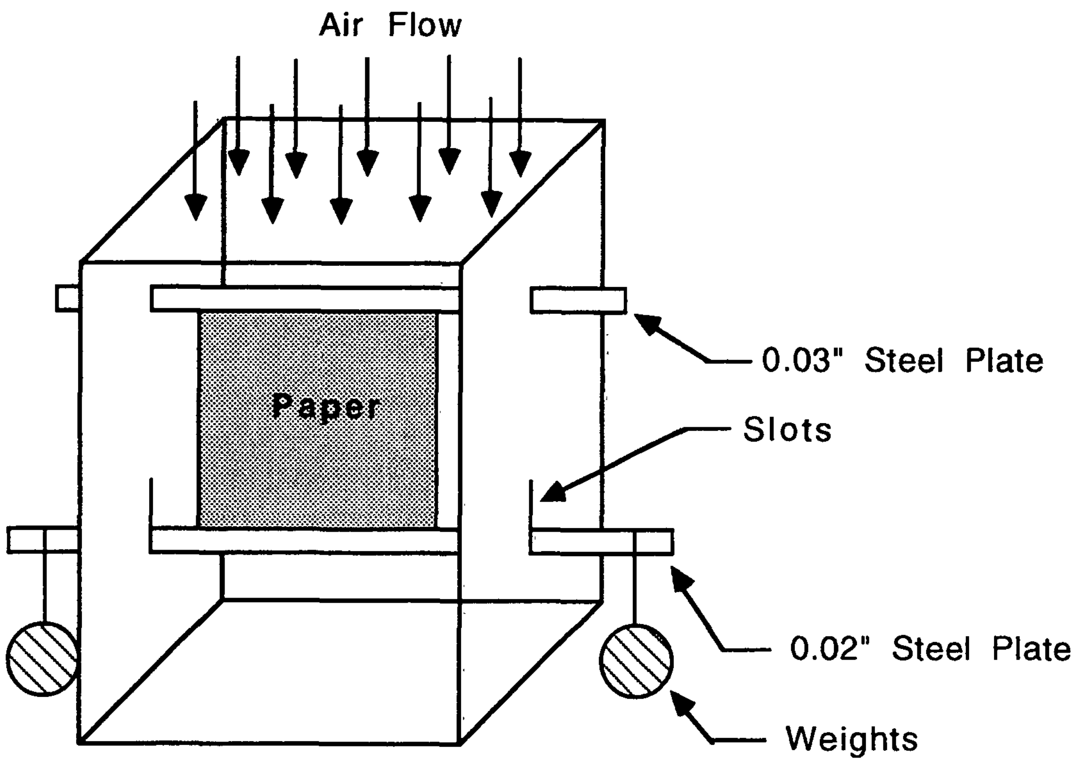
A privately funded nonprofit graduate university

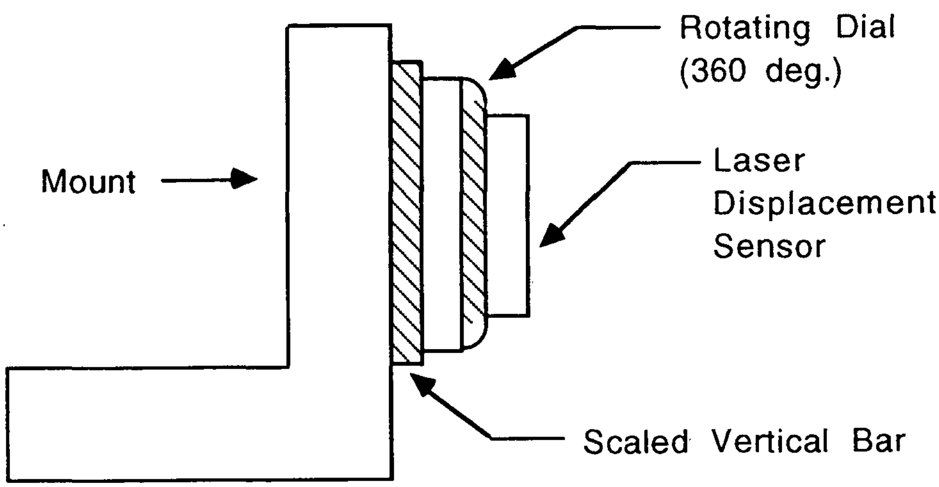
RATIONALE AND OBJECTIVES

1. Analyze the aerodynamics and structural mechanics of sheet flutter

2. Correlate the onset of break or sheet damage "threshold" with the relevant parameters

SCHEMATIC OF THE TEST SECTION





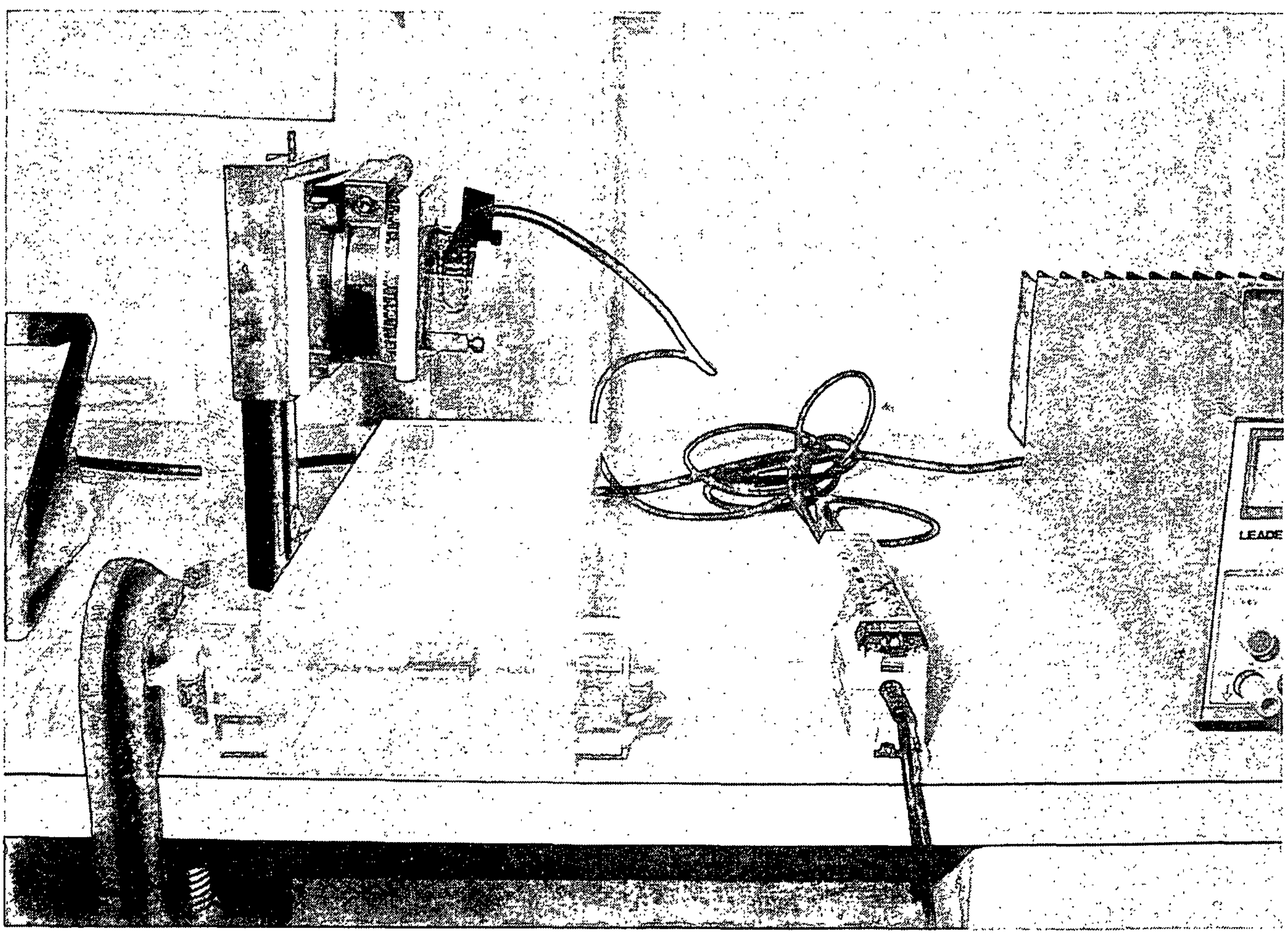
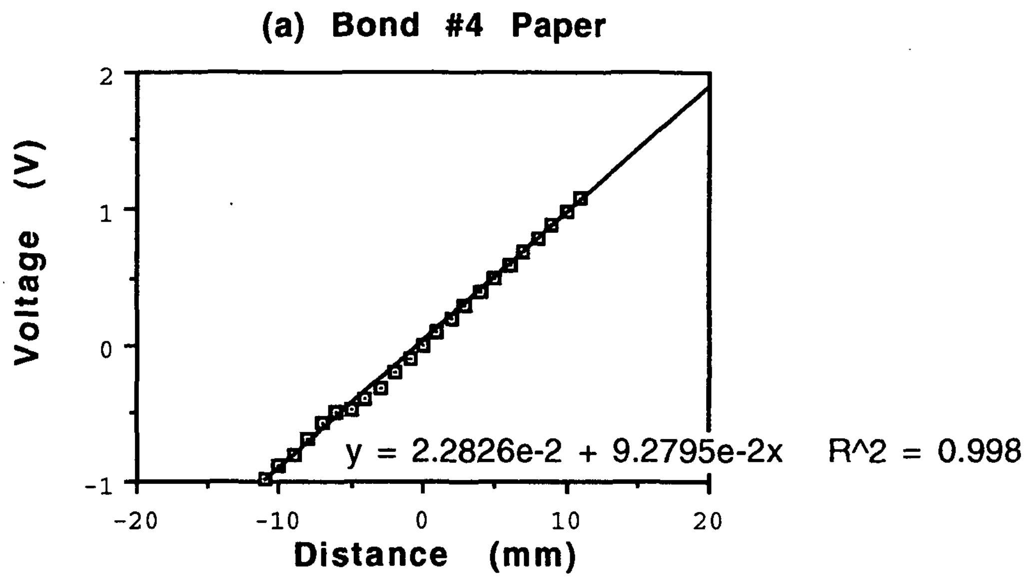
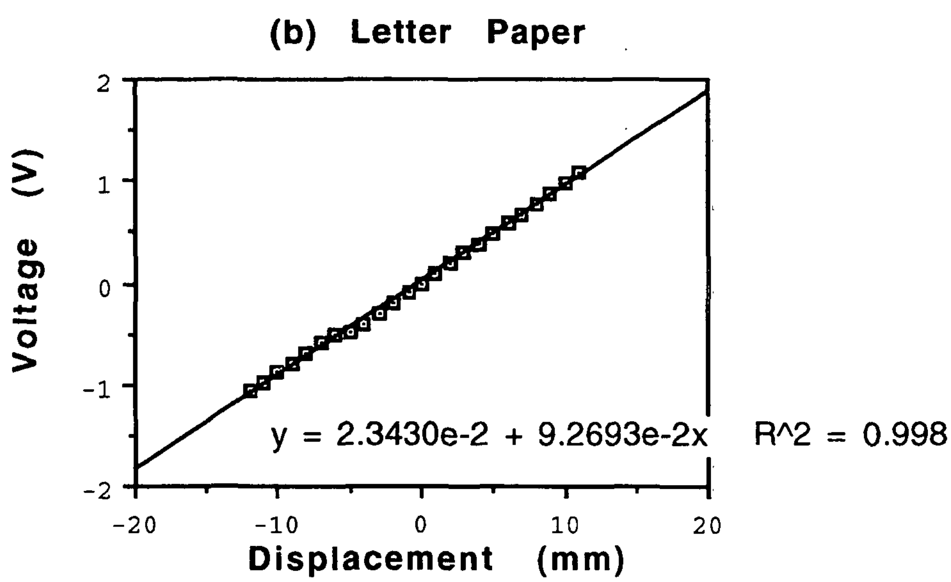
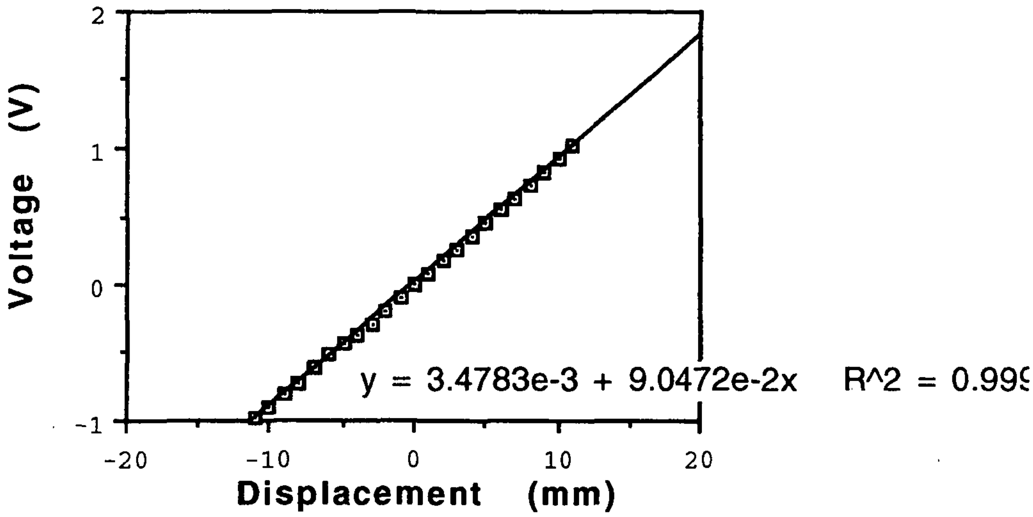


Figure 2. Calibration for the Laser Displacement Sensor.

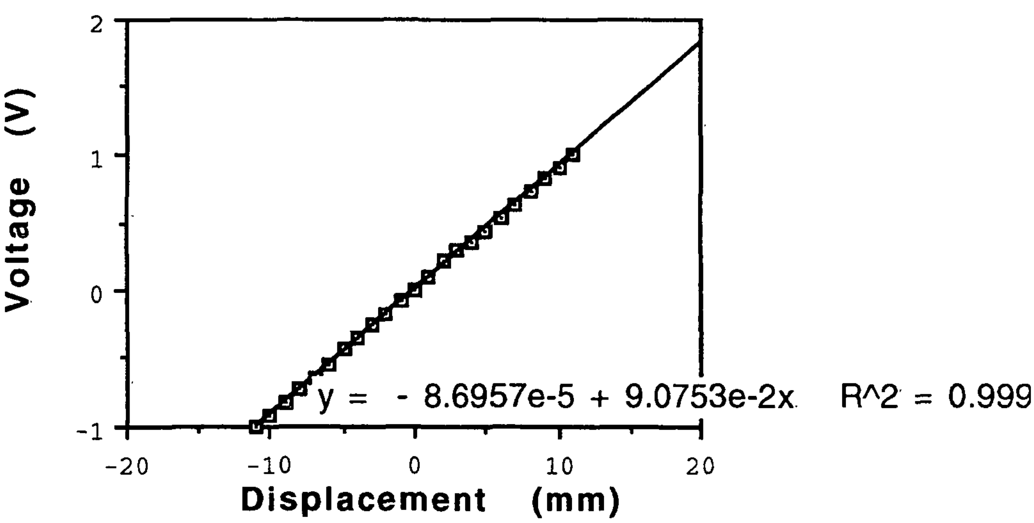

(a) Bond #4 Paper
Voltage (V)
2
1
0
-1
-20
-10
0
10
20
Distance (mm)
y = 2.2826e-2 + 9.2795e-2x R^2 = 0.998

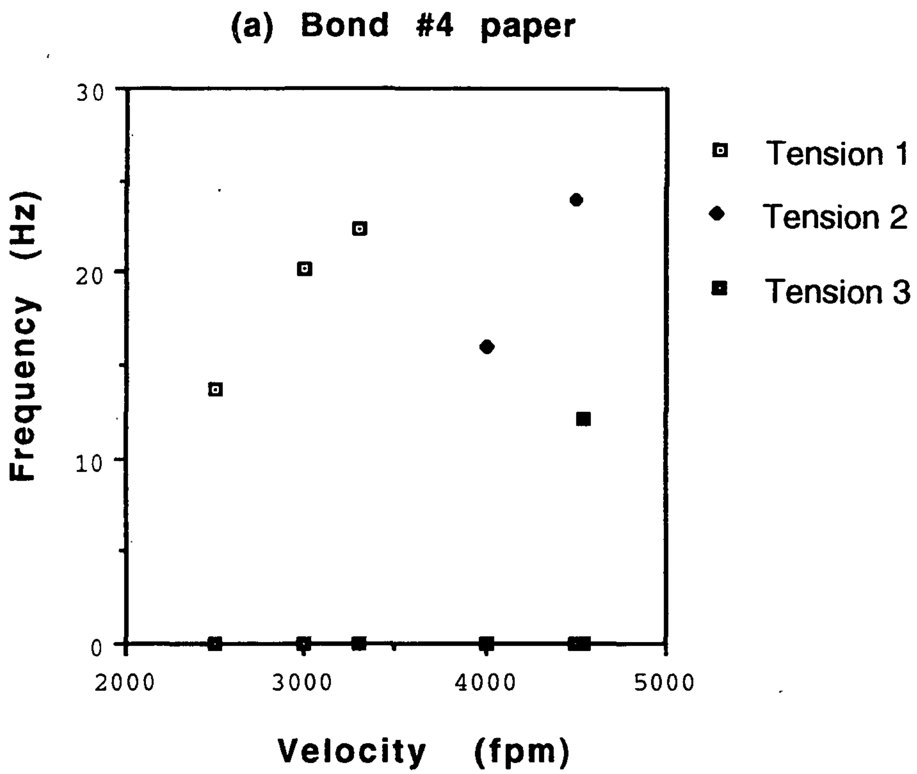

(b) Letter Paper
Voltage (V)
2
1
0
-1
-2
-20
-10
0
10
20
Displacement (mm)
y = 2.3430e-2 + 9.2693e-2x R^2 = 0.998

(c) Corrugating Medium (unbleached paperboard)

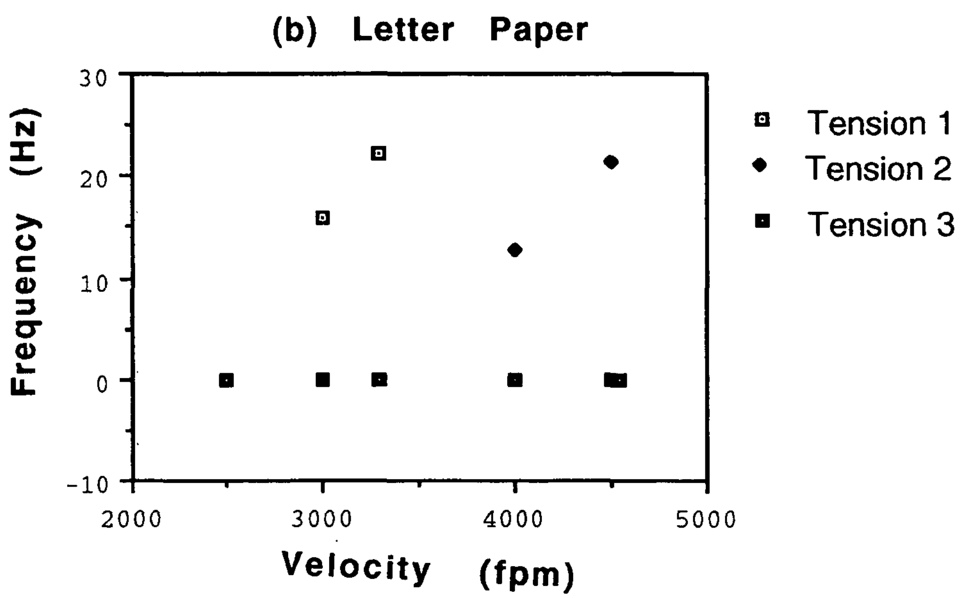


(d) Trace Paper



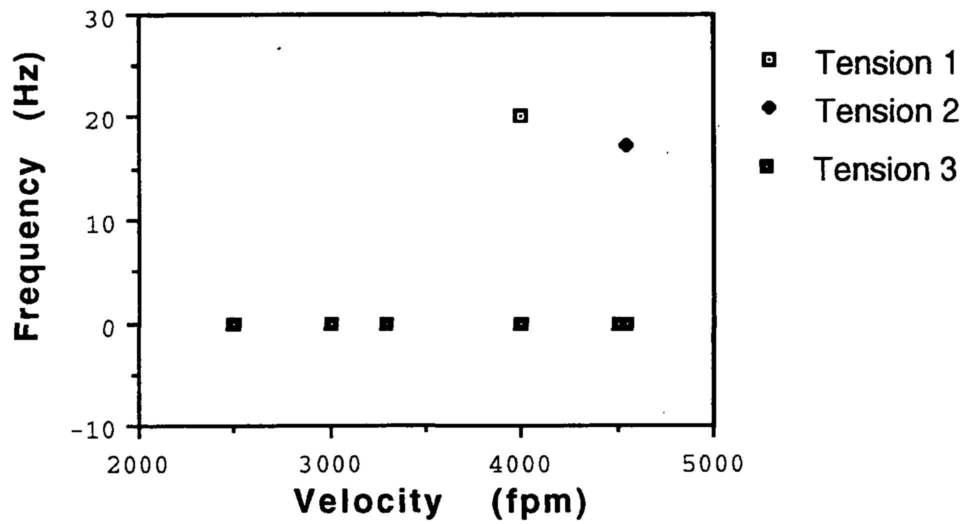


(a) Bond #4 paper
Frequency (Hz)
30
20
10
0
2000
3000
4000
5000
Velocity (fpm)
Tension 1
Tension 2
Tension 3

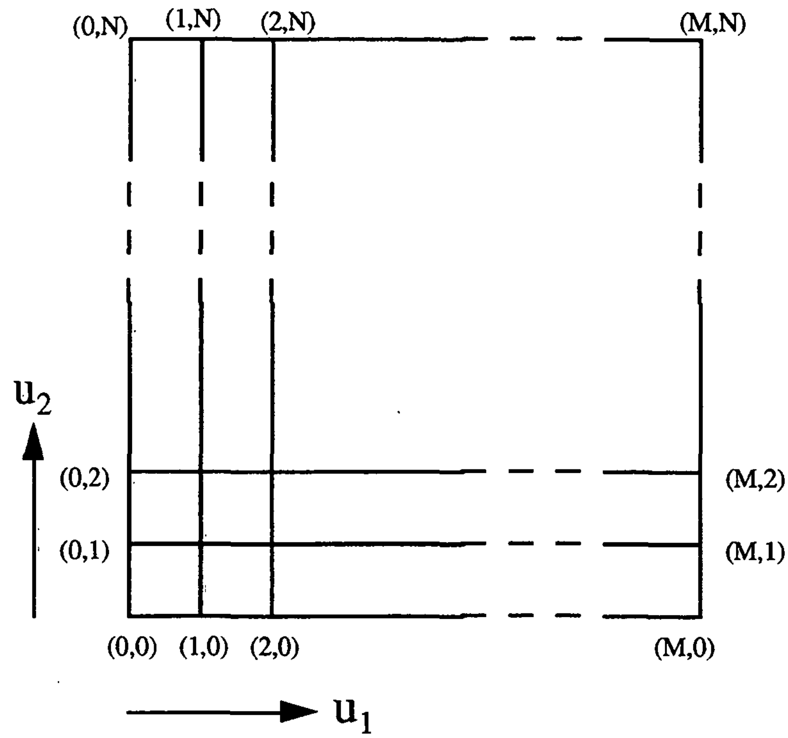


(b) Letter Paper
Frequency (Hz)
30
20
10
0
-10
2000
3000
4000
5000
Velocity (fpm)
Tension 1
Tension 2
Tension 3

(c) Corrugating Medium (unbleached paperboard)



CONTROL POINT POSITIONS AND MATERIAL COORDINATE



FUTURE GOALS and TASKS:

1. Wind Tunnel Experiments

- Measurement of the onset of sheet flutter and its frequency as a function of air velocity and tension.

FUTURE GOALS and TASKS (cont'd)

2. Analyses:

a. Continue the implementation of a thin shell finite element code (steady state, 3-dimensional, linear, isotropic material behavior) with sheet under tension on bottom and top edges and subject to gravity.
b. Modification of part (a) to consider non-linear and non-isotropic material behavior.

FUTURE GOALS and TASKS (cont'd)

2. Analyses (cont'd)

c. Analysis of the effects of time-dependent boundary conditions.
d. Fluid dynamics analysis and computation of lift and drag on surface with varying angles.
e. Coupling of the solid-fluid effects. The excitation force is replaced by a lift and drag induced force.

3. Optimization

PAPERMAKING

DISPLACEMENT DEWATERING

PROJECT 3680

April 27, 1993
Institute of Paper Science and Technology
Atlanta, Georgia

DISPLACEMENT DEWATERING

By

Jeffrey Lindsay
Associate Professor of Engineering

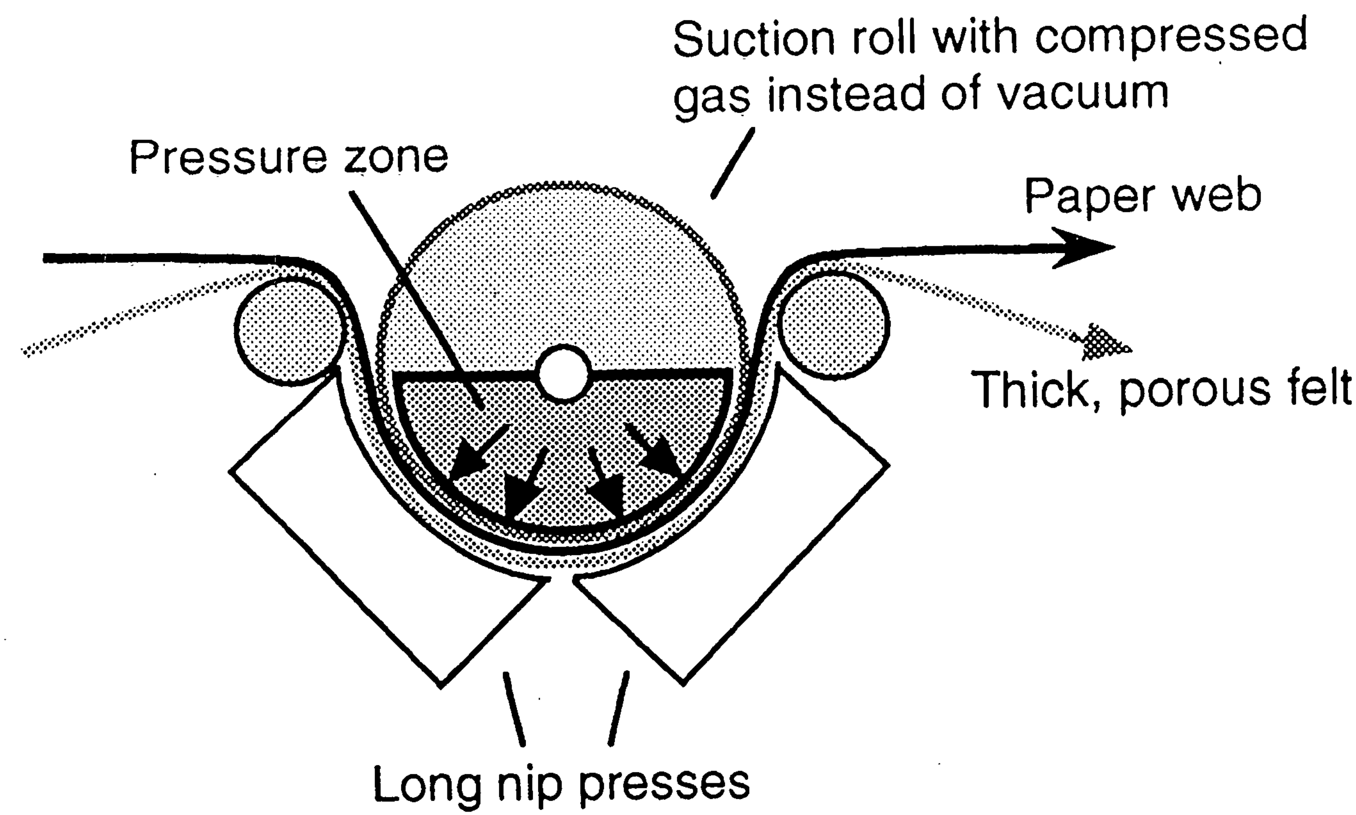


Figure 1. Possible implementation of the displacement dewatering concept.

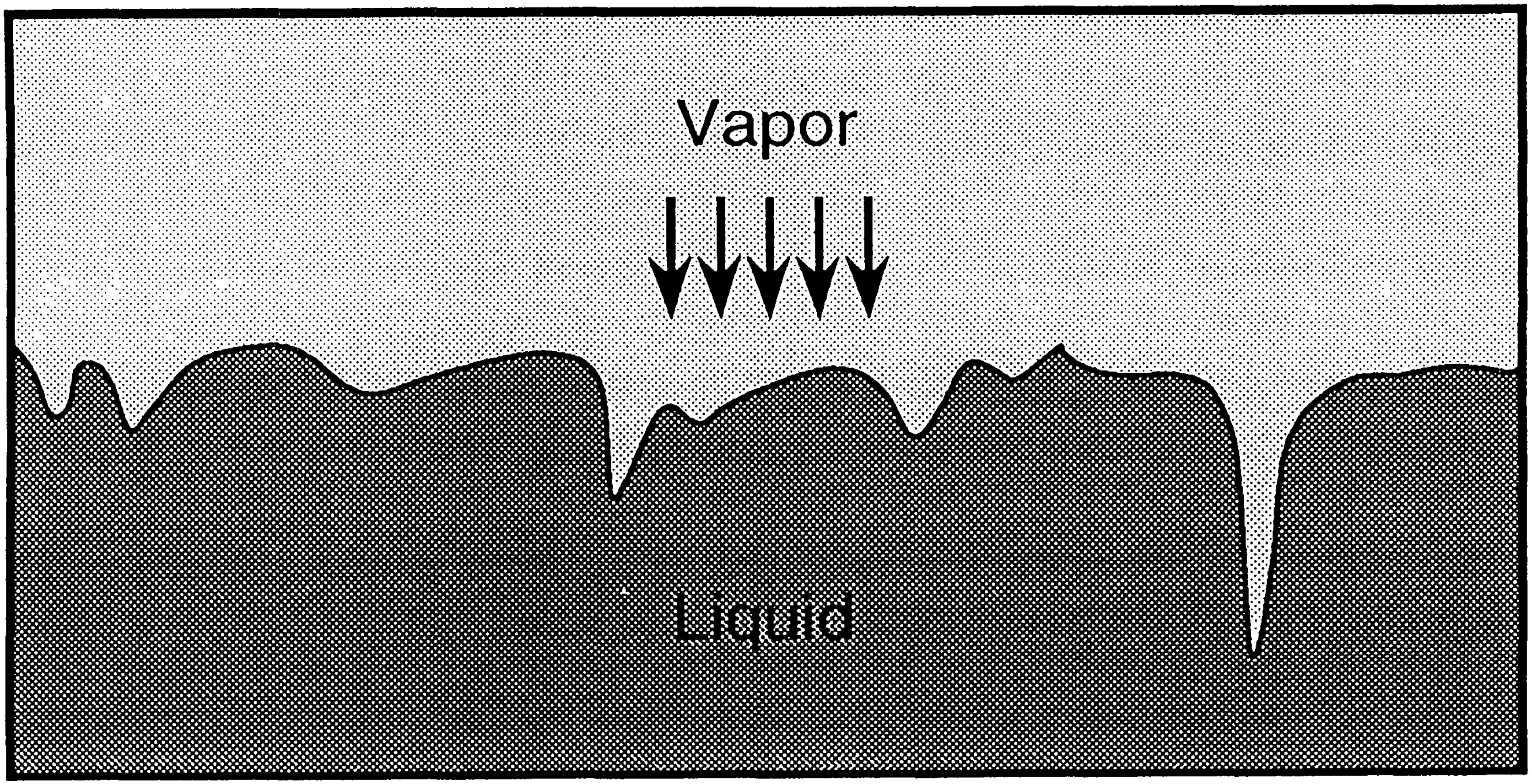


Figure 2. Viscous fingering in a porous medium as a gas displaces a liquid.

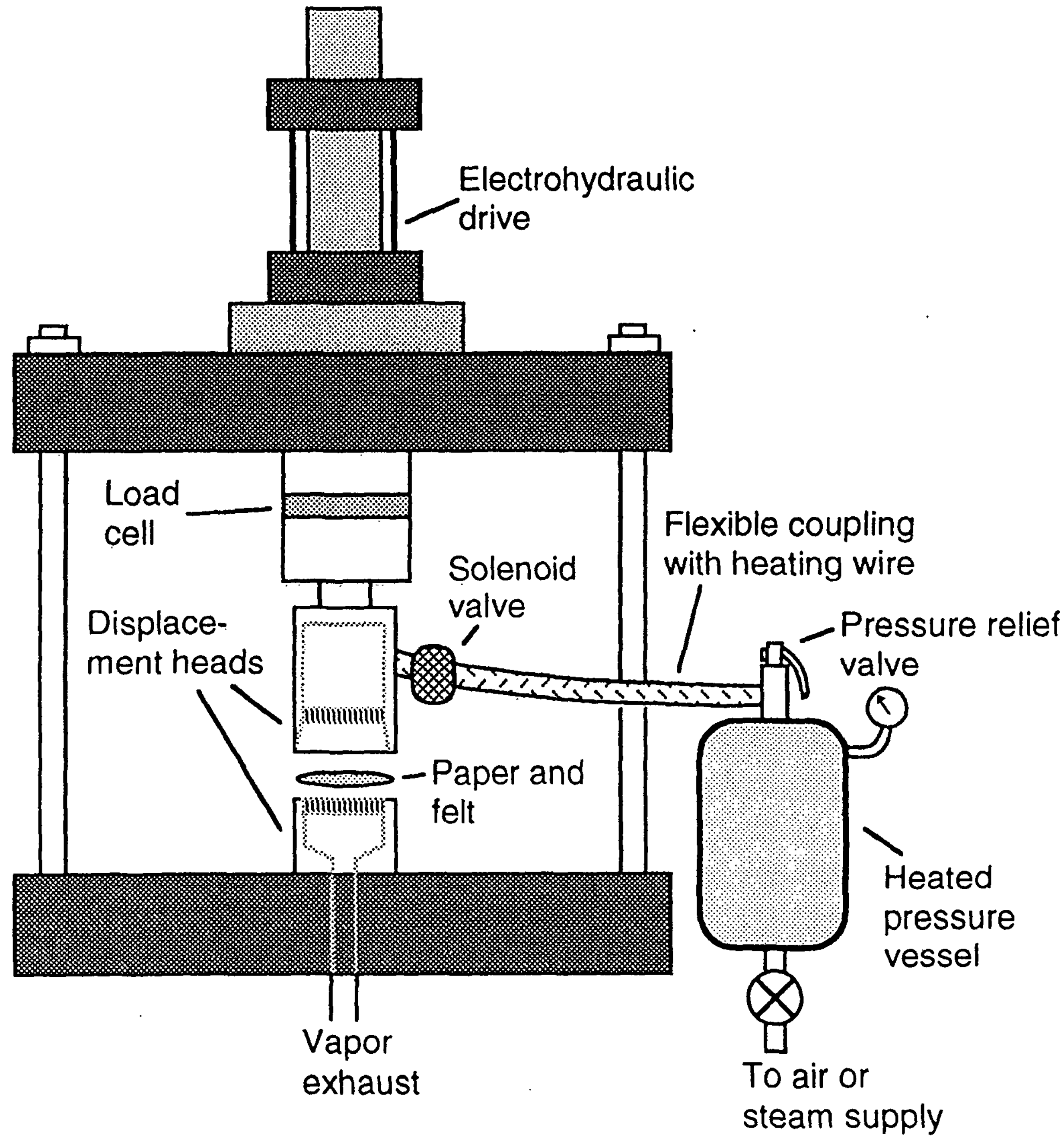


Figure 3. The experimental displacement apparatus.

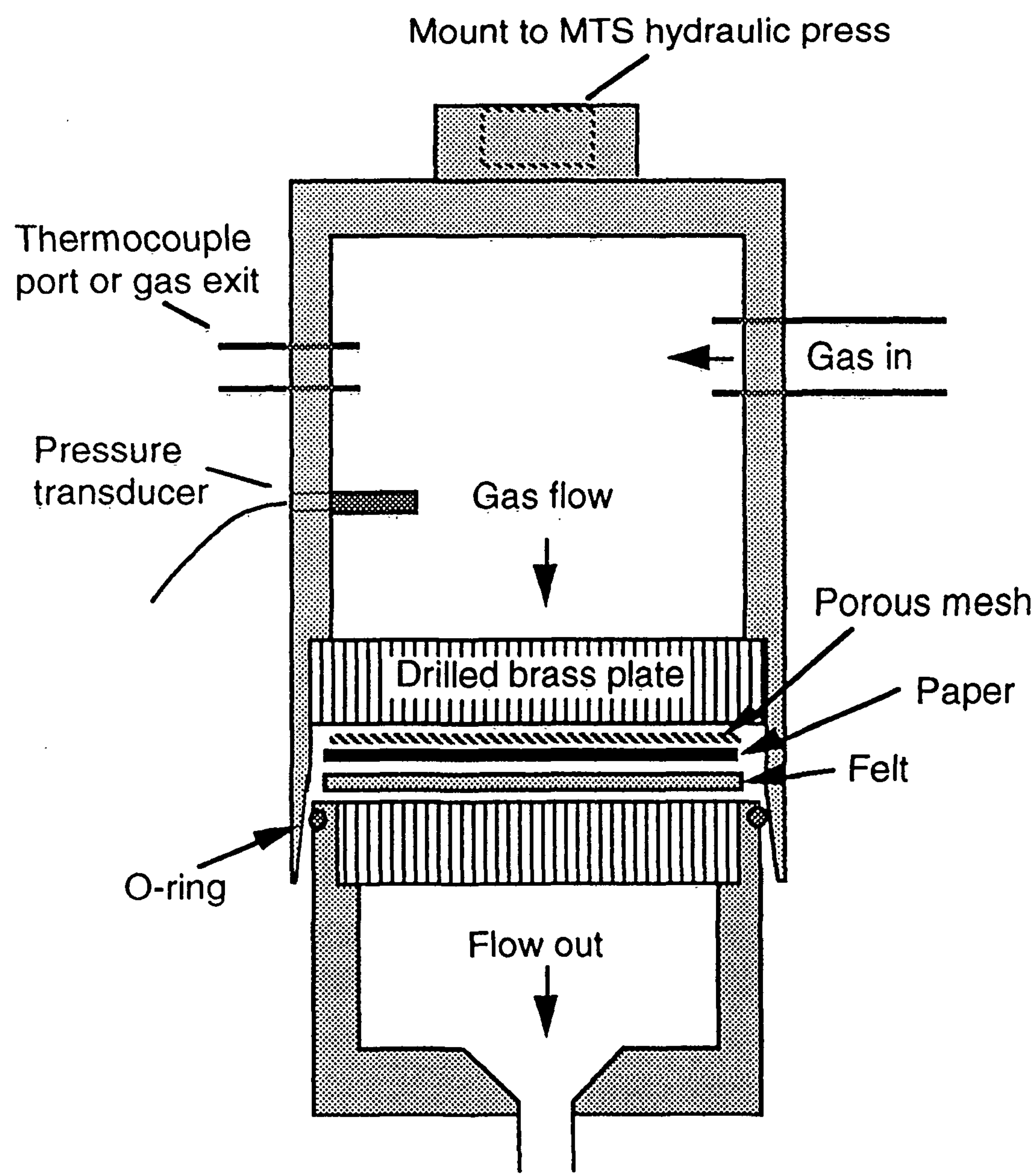


Figure 4. Detail of the displacement heads.

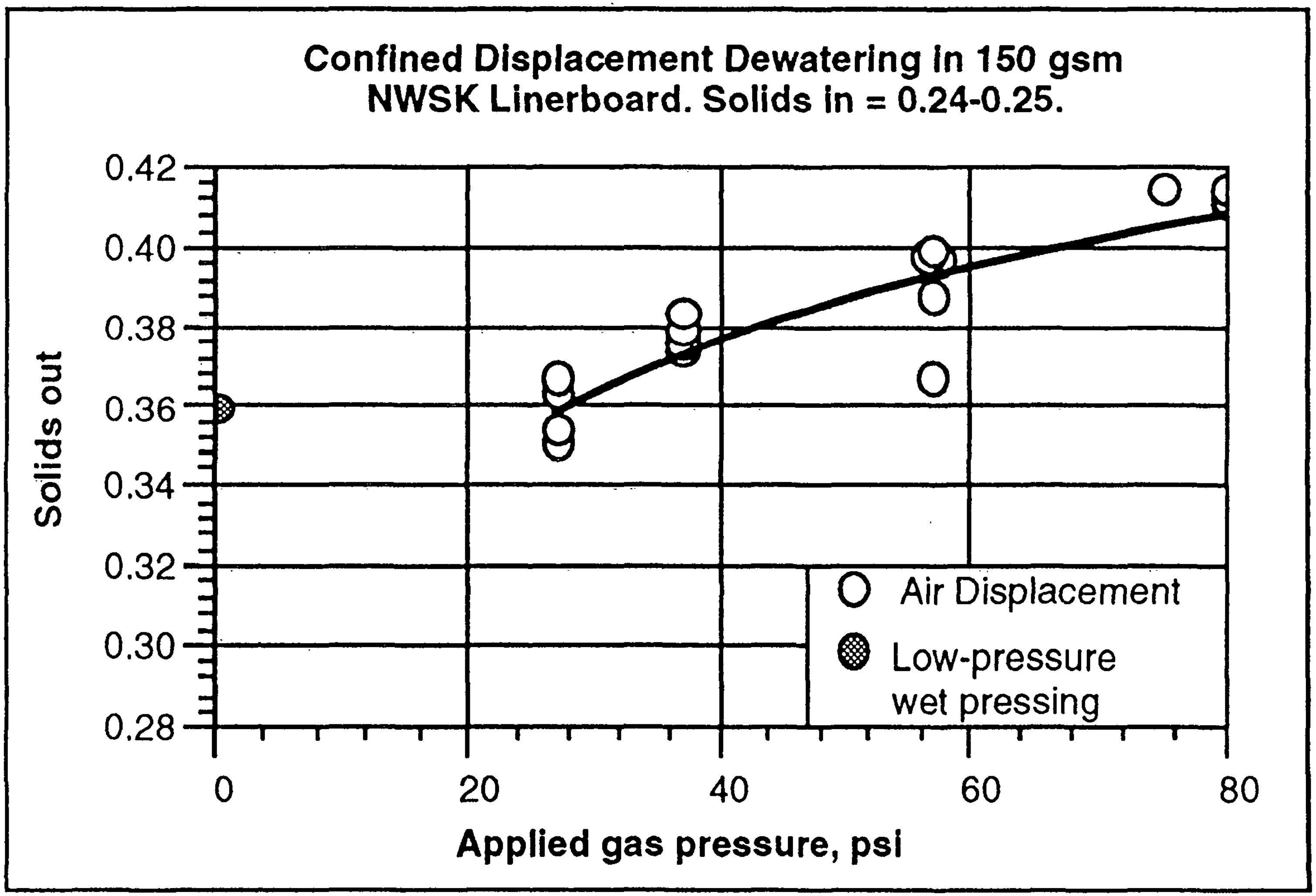


Figure 5. Confined air displacement in 150 gsm NWSK sheets.

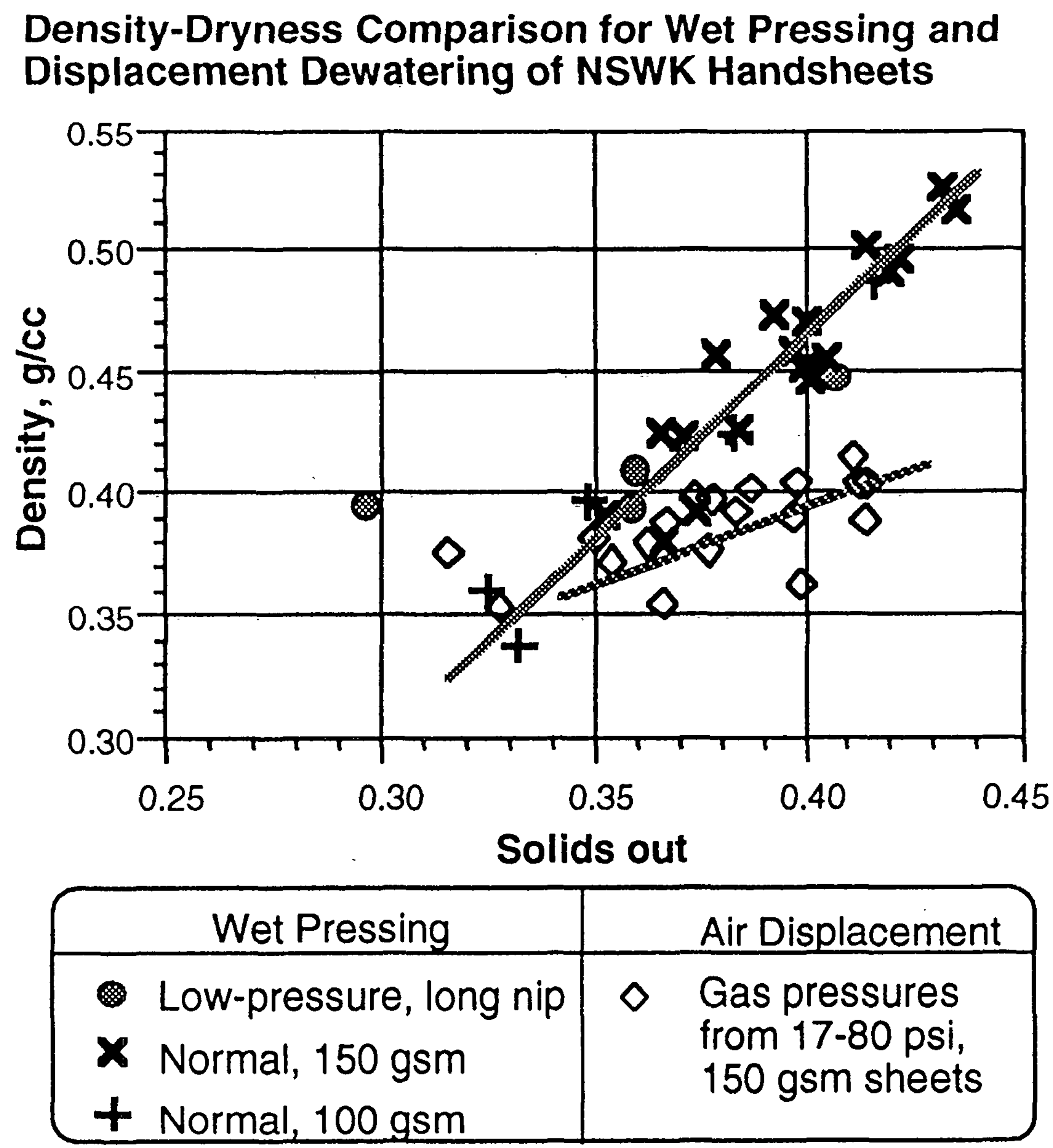


Figure 6. Density-dryness relationships for wet pressing and displacement dewatering in Northern softwood unbleached kraft handsheets. Solids in = 23-25%.

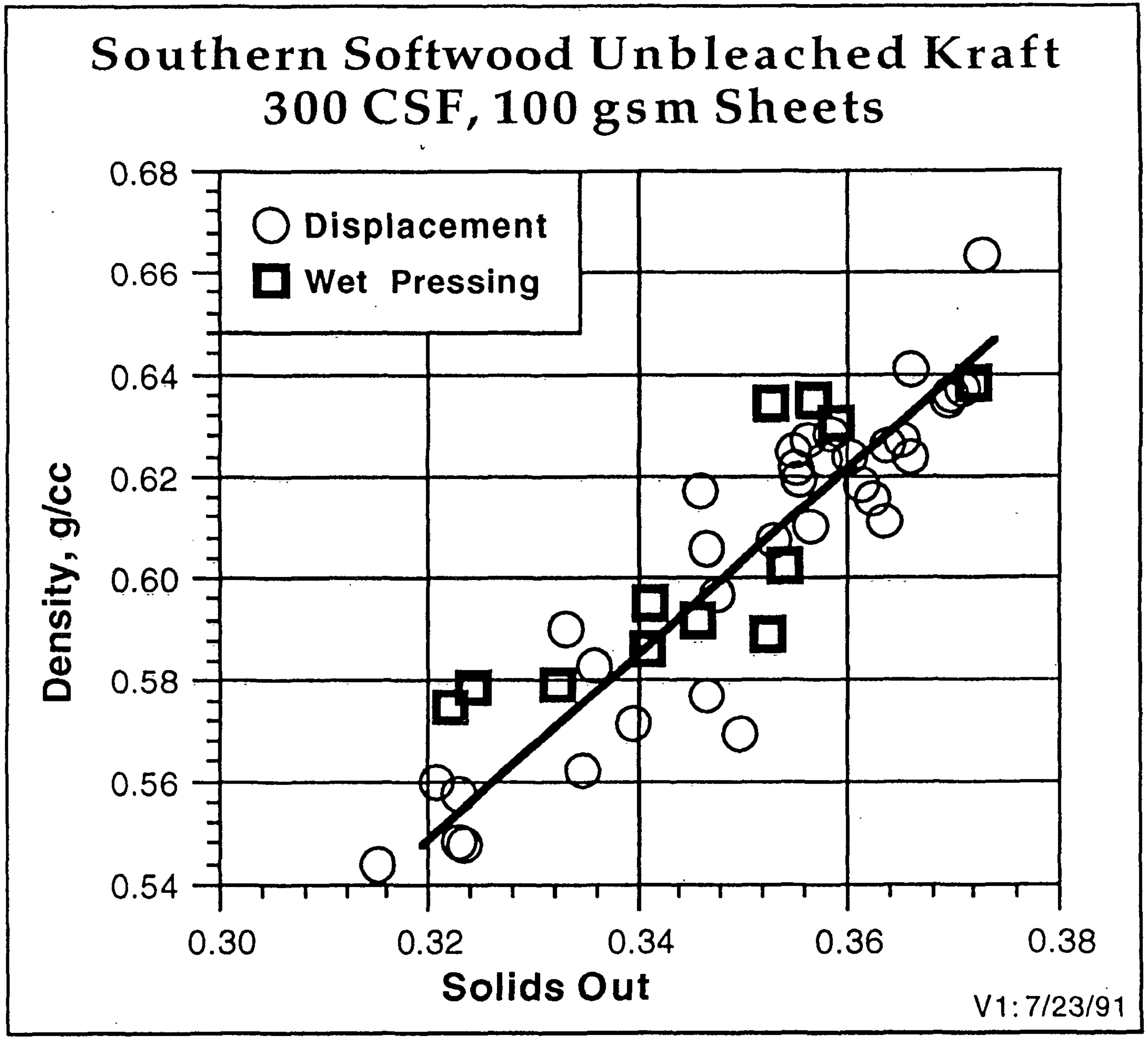


Figure 7. Density-dryness relationships in an unbleached southern softwood kraft pulp, 300 ml CSF.

PAPERMAKING

FUNDAMENTALS OF WATER REMOVAL PROCESSES

PROJECT 3480

April 27, 1993
Institute of Paper Science and Technology
Atlanta, Georgia

FUNDAMENTALS

OF

WATER REMOVAL

PROCESSES

By

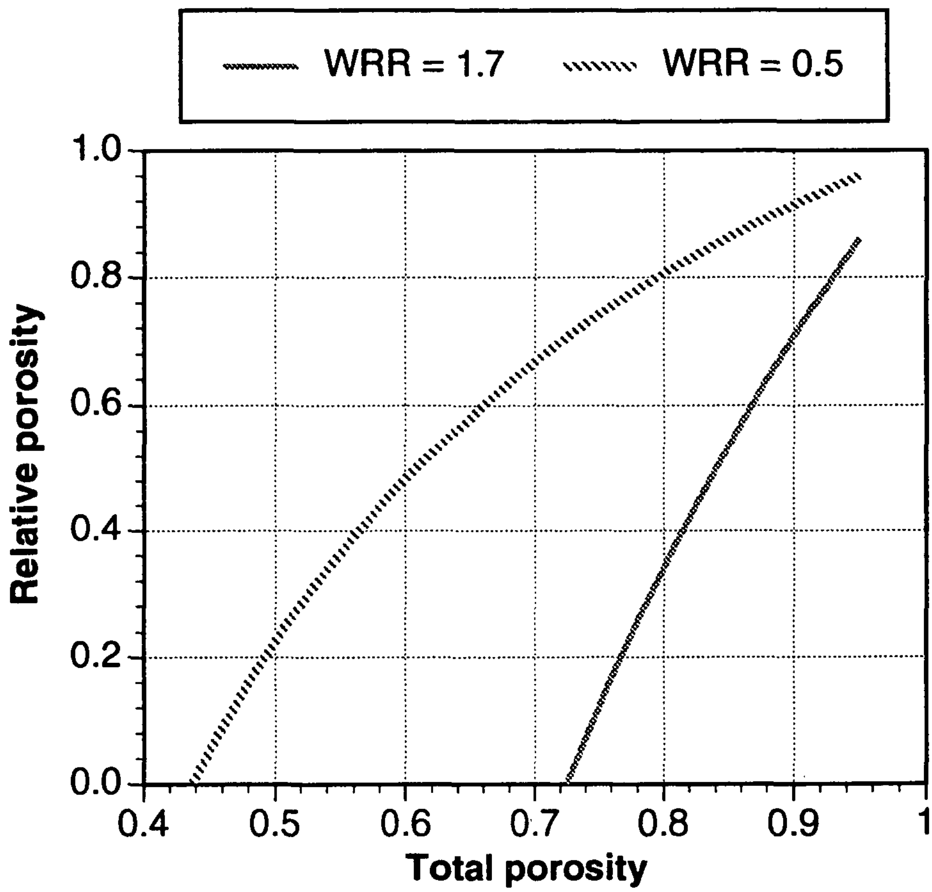
Jeffrey Lindsay
Associate Professor of Engineering

Term	Definition
Total porosity, ε	Volume fraction of pore space, or 1 - volume fraction of solid matrix
Effective flow porosity, ε_{eff}	Volume fraction of pore space open to flow
Relative flow porosity, ε_{rel}	Fraction of the total pore space that is open to flow: $\varepsilon_{rel} = \varepsilon_{eff}/\varepsilon$
Extrafiber porosity, ε_o	Volume fraction of pore space between swollen fibers, or 1 - volume fraction of swollen fibers

Table 1. Porosity Definitions.

Water Retention Ratios

$$\varepsilon_{rel} = 1 - WRR \, \frac{\rho_s}{\rho_l} \left(\frac{1-\varepsilon}{\varepsilon} \right)$$



Estimated relative porosities from the WRR relationship.

Kozeny-Carman Analysis

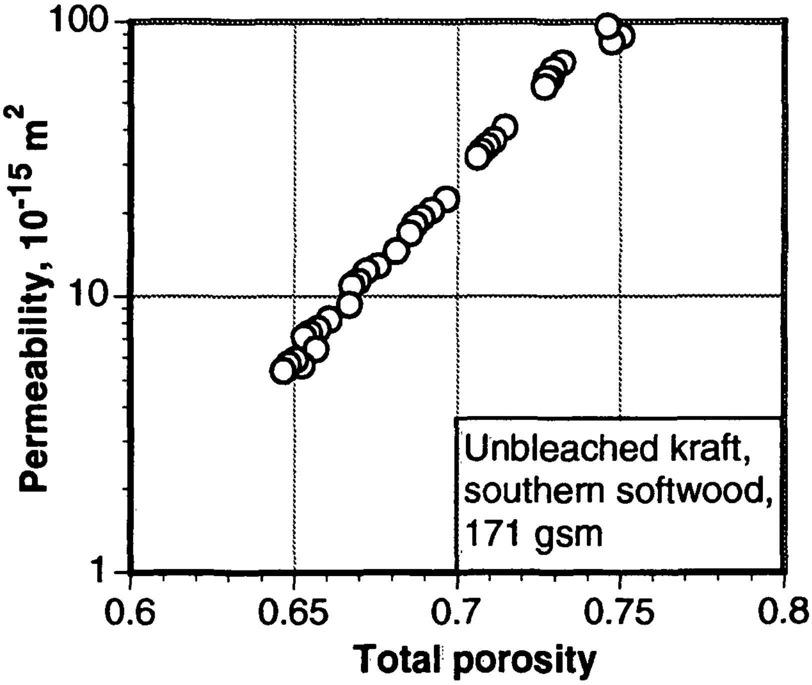
$$v = \frac{K}{\mu}\frac{\Delta P}{L}$$

$$K = \frac{1}{\kappa S_o^2}\,\frac{\varepsilon_o 3}{(1-\varepsilon_o)^2}$$

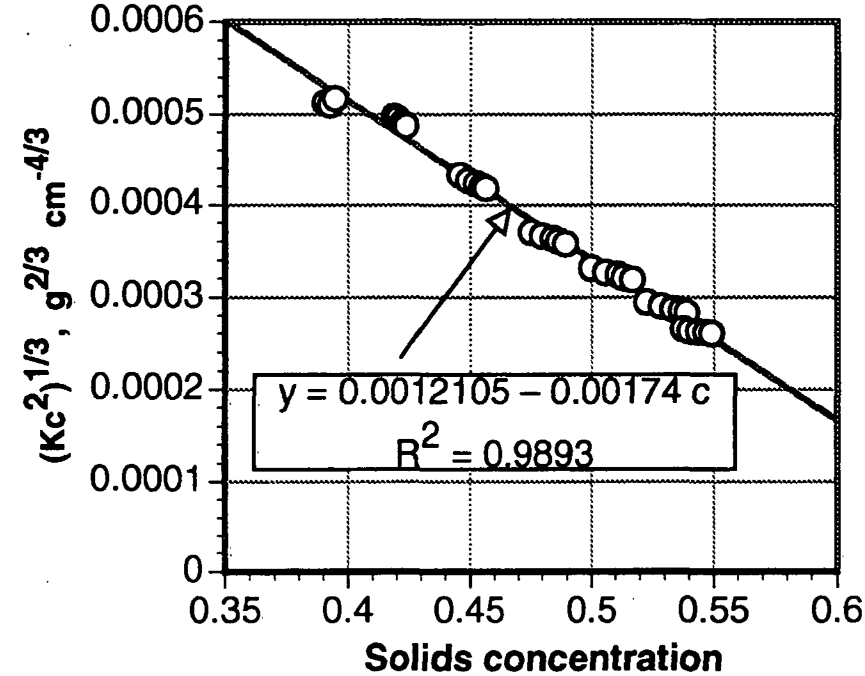
$$\varepsilon_o = 1 - \alpha c$$

$$K = \frac{1}{5.55 S_o^2}\,\frac{(1-\alpha c)^3}{\alpha^2 c^2}$$

$$(Kc^2)^{1/3} = \left(\frac{1}{5.55\ S^2}\right)^{1/3}(1-\alpha c)$$

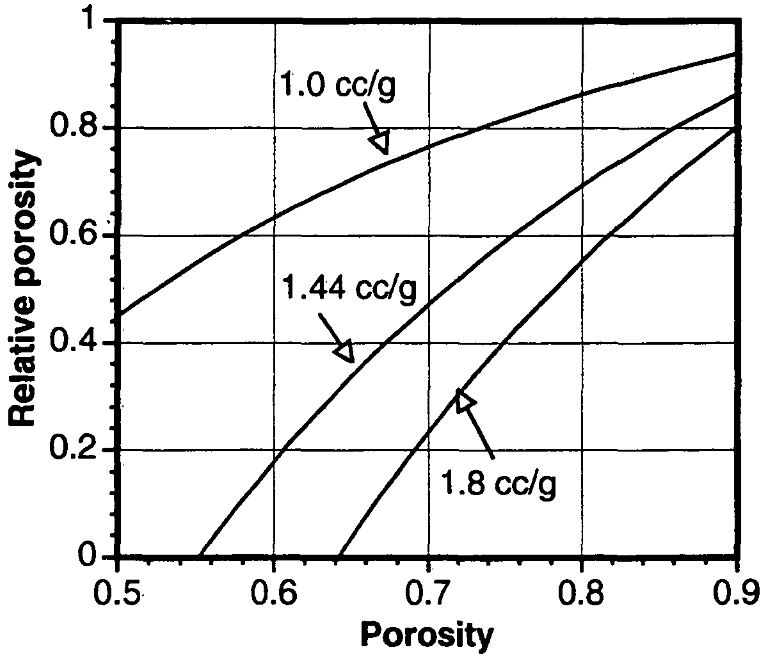


Permeability data for a handsheet of unbleached kraft pulp.



Permeability data replotted for Kozeny-Carman analysis.

$$\varepsilon_{rel} \approx \frac{\varepsilon_o}{\varepsilon} = \frac{1-\alpha c}{\varepsilon} = \frac{1-\alpha \rho_s (1-\varepsilon)}{\varepsilon}$$

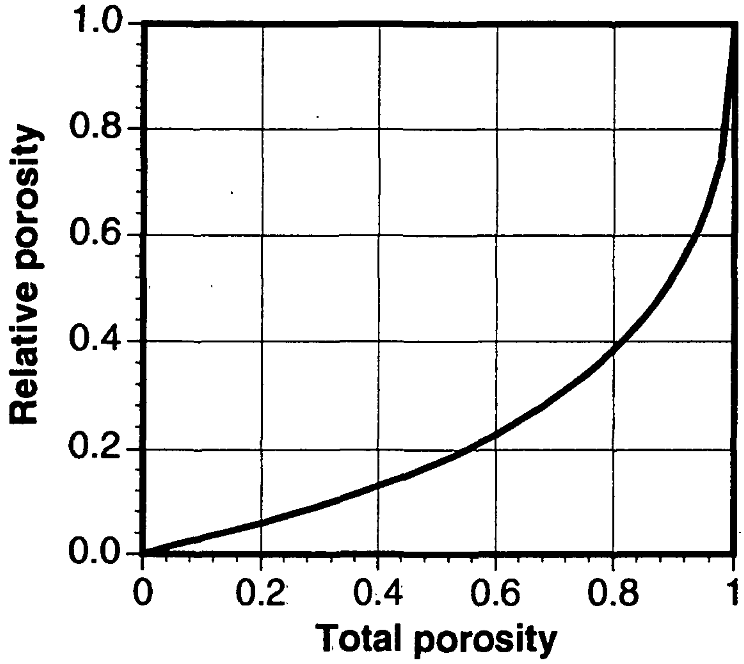


Relative porosity in paper based on Kozeny-Carman analysis using typical specific volume results.

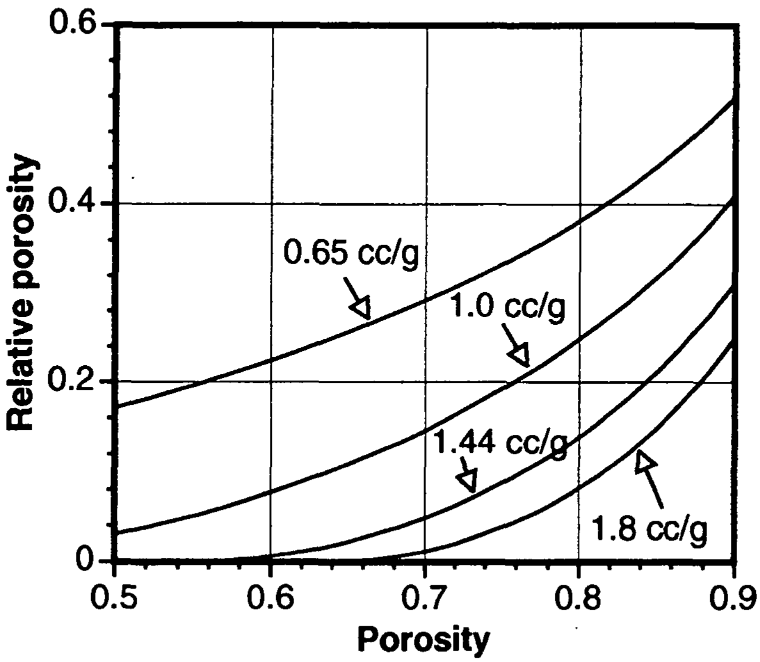
Kyan's Geometrical Model

$$\varepsilon_{eff} = N_e^2(1-\varepsilon)\ (0.5/\pi)$$

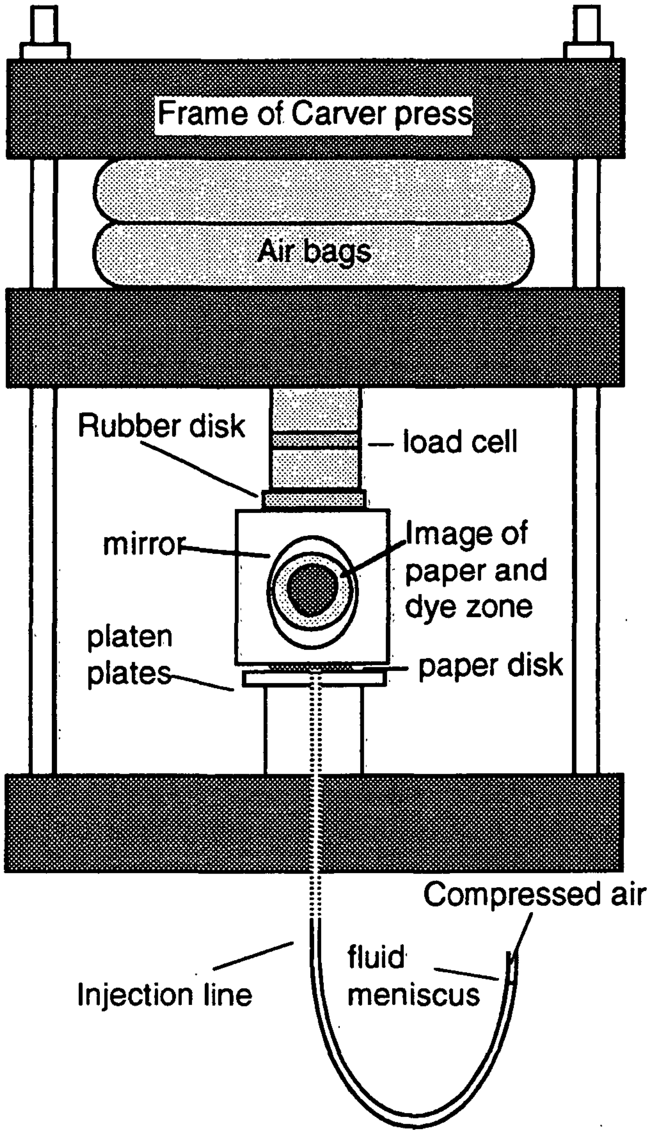
$$N_e = \left(\frac{\pi}{0.5(1-\varepsilon)}\right)^{1/2} - 2.5$$



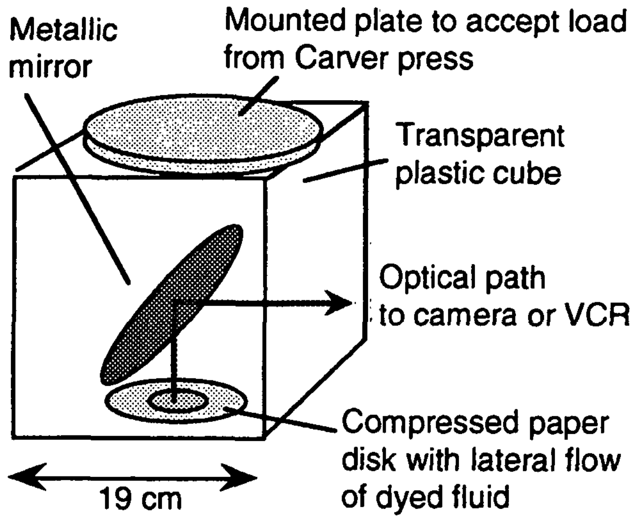
Predicted relative porosity based on the approach of Kyan et al.



Relative porosity results based on a combination of Kyan's model and extrafiber porosity analysis using typical specific volume values. Unhydrated fiber corresponds to $\alpha = 0.65$ cc/g.

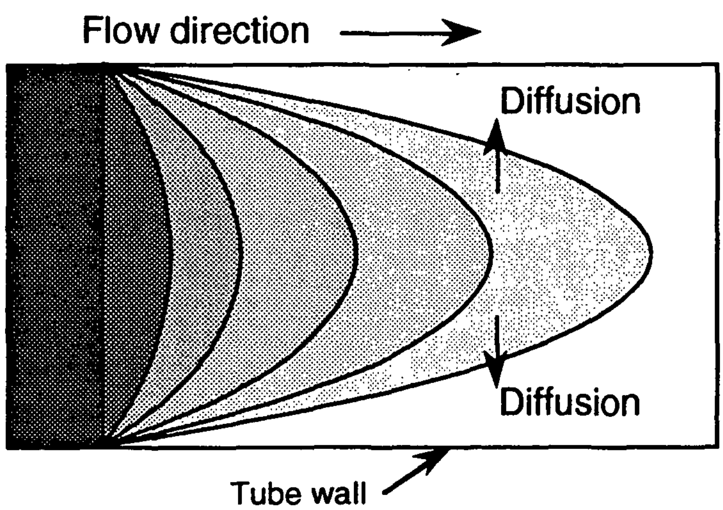


Modified lateral flow apparatus for dye injection tests.

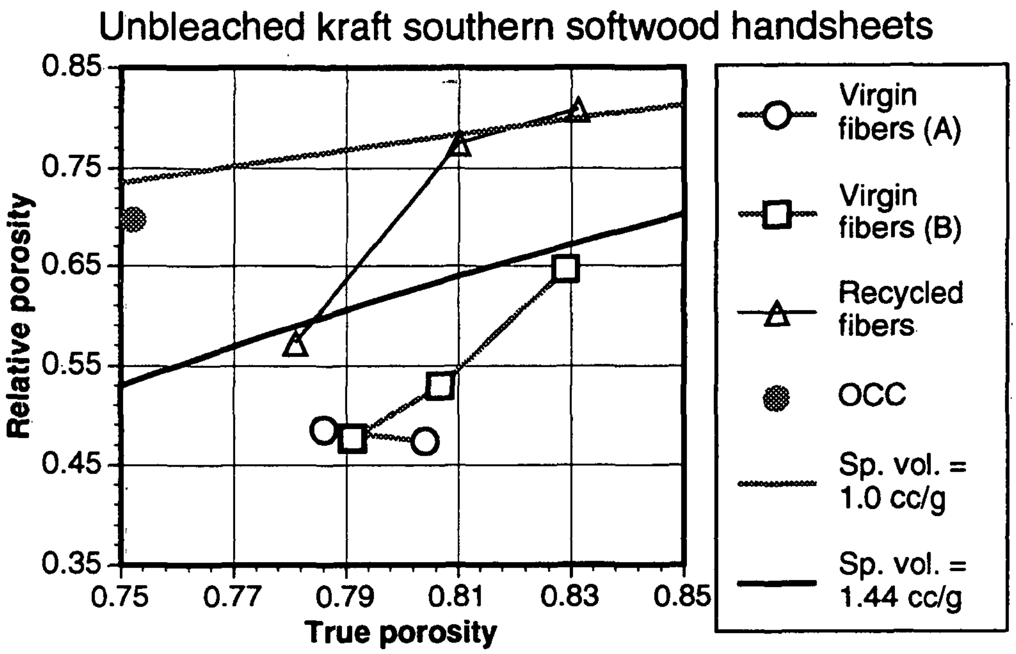


Plastic pressing block with mirror for optical access to a compressed sheet.

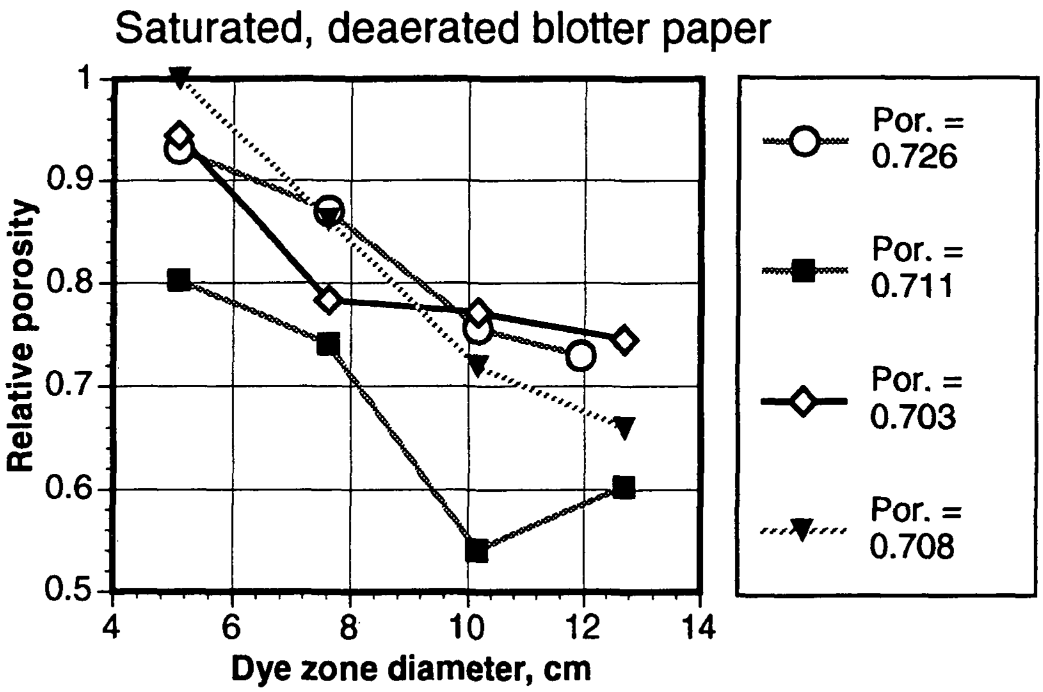
$$\varepsilon = 1 - \frac{BW}{\rho_c L}$$



Distortion of a flat dye-water boundary moving in a flow with a parabolic velocity profile. Some of the dye advances faster than the average flow velocity.



FRelative porosity in virgin and recycled unbleached kraft sheets. Extrafiber pore space curves are also shown.



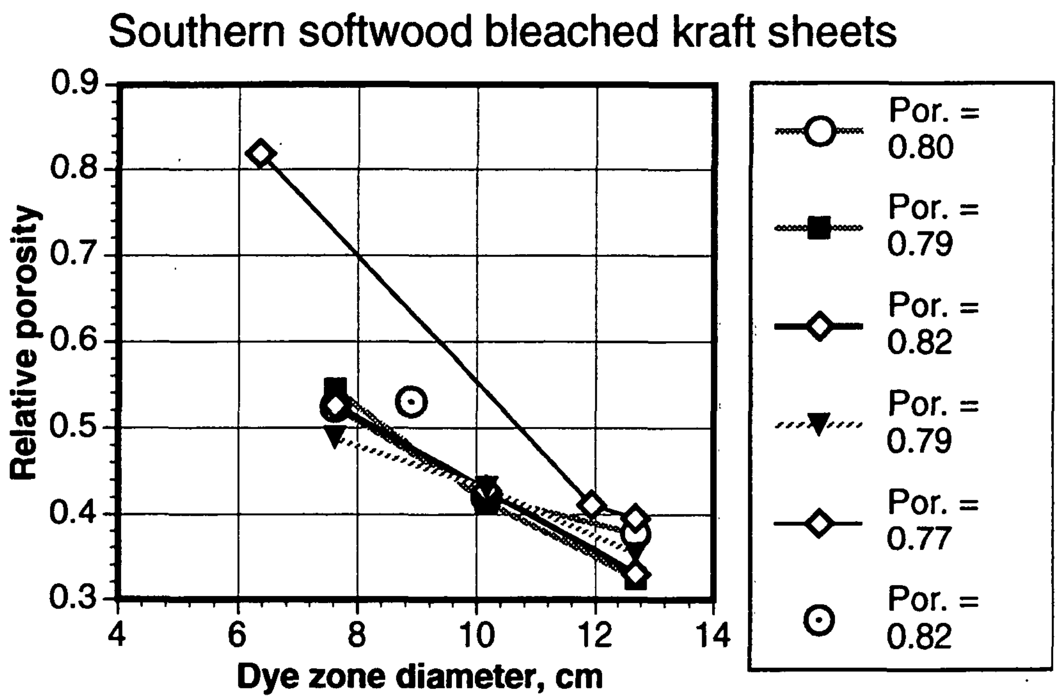
Relative porosity results in saturated blotter paper as a function of dye zone diameter injected into the sheet.

Total porosity	Relative porosity
0.814	0.471
0.817	0.454
0.815	0.446
0.817	0.465
0.812	0.458
AVG:	**0.459**

Replicate relative porosity values for tests with handsheets of never-dried bleached southern softwood kraft pulp.

Total porosity	Relative porosity
0.825	0.535
0.766	0.396

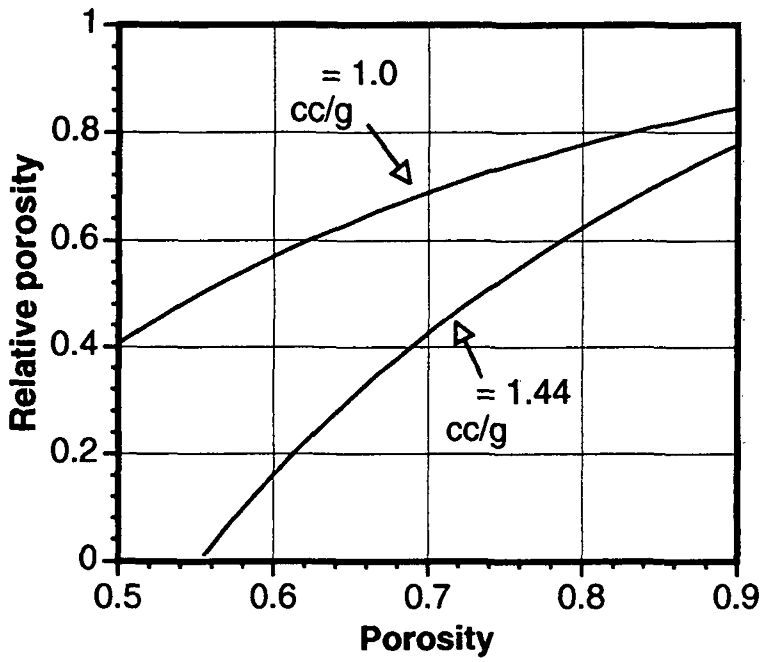
Replicate relative porosity values for tests with handsheets of never-dried bleached southern softwood kraft pulp.



Relative porosity versus dye diameter in bleached kraft handsheets.

Series I		Series II		Series III	
ε	Dry ε_{rel}	ε	Dry ε_{rel}	ε	Dry ε_{rel}
0.771	0.936	0.778	0.583	0.649	0.699
0.773	0.836	0.777	0.712	0.647	0.854
0.769	0.974	0.782	0.747	0.656	0.891
0.771	1.004	0.777	0.668	0.648	0.801
0.772	0.933	0.778	0.803	0.649	0.962
0.768	0.810				
AVG:	**0.916**	**AVG**	**0.703**	**AVG**	**0.841**

Dry (apparent) relative porosity from injection into dry blotter paper sheets.



Predicted relative porosity results based on 90% of extrafiber pore space being open to flow.

CONCLUSIONS

Most of the extrafiber pore space in paper exists as interconnected pores, accessible to flow.

Dead end pores are estimated to comprise less than 10% of the extrafiber pore space.

The Kyan model for relative porosity appears to underpredict relative porosity values in real fibrous structures.

Relative porosity measurements in the thickness direction of paper still pose serious experimental challenges.

PAPERMAKING

FUNDAMENTALS OF DRYING

PROJECT 3470

April 27, 1993

Institute of Paper Science and Technology
Atlanta, Georgia

FUNDMENTALS OF DRYING

By

David Orloff
Professor of Engineering

FUNDAMENTALS OF DRYING

Project Number:3470

David Orloff

PROGRAM OBJECTIVE:

With joint DOE support, to develop an understanding and a database sufficient for the commercialization of impulse drying of paper.

RESEARCH OBJECTIVES:

1) Demonstrate that impulse drying is superior to alternate technologies (double felted pressing).

2) Demonstrate that press felts can be expected to survive impulse drying.

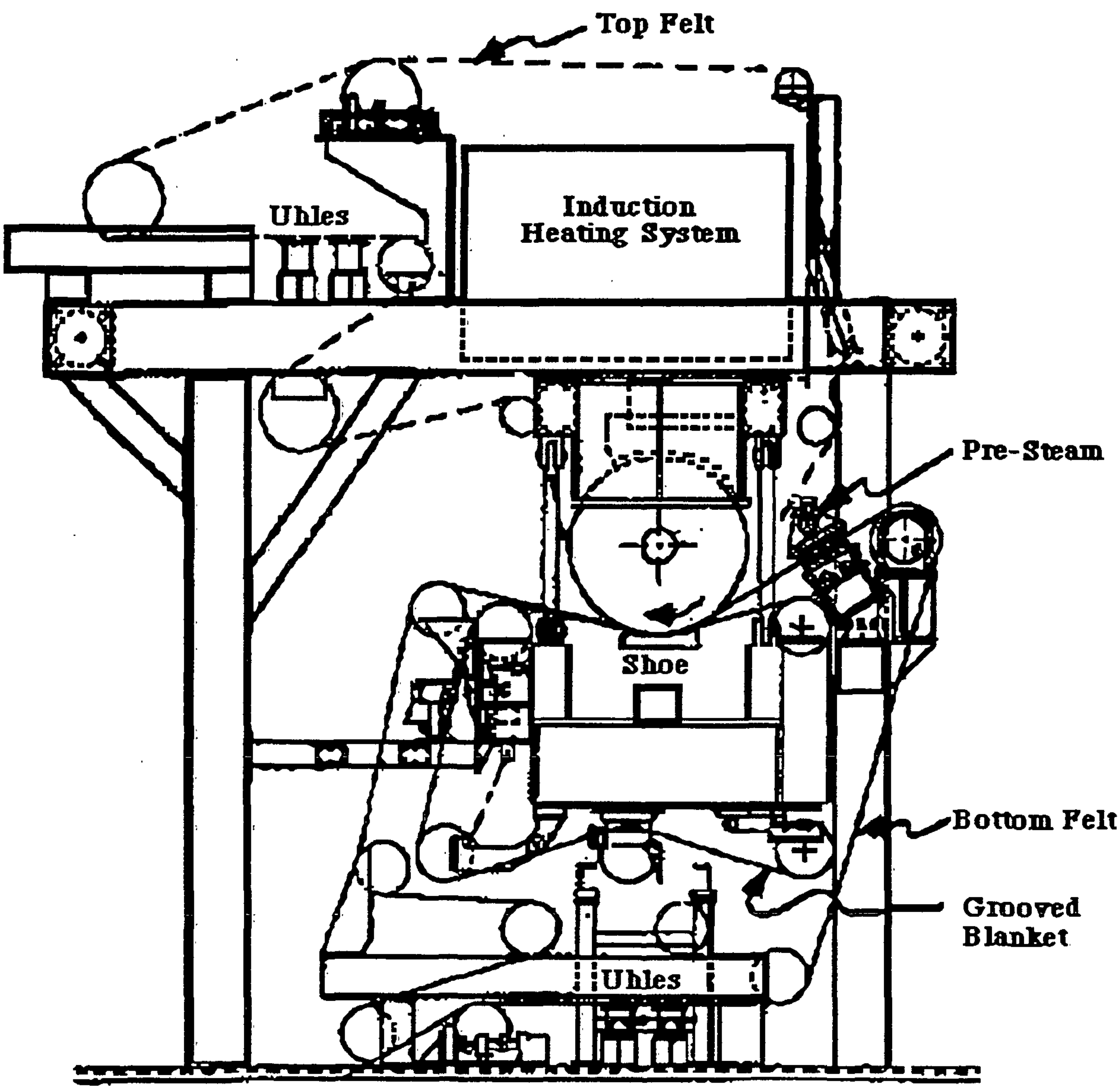
3) Determine the optimum structure of multi-ply sheets to allow extensive replacement of virgin pulp with recycled pulp.

4) Determine if modifications to pressure pulse shape influence optimum impulse drying operating conditions and resulting press dryness, physical property development and energy use.

5) Determine the range of basis weights over which impulse drying is superior to double felted pressing.

COMPARISON OF IMPULSE DRYING TO DOUBLE FELTED PRESSING

In March of 1992 batch-pilot experiments with single-ply linerboard, on the Beloit Corporation's extended nip shoe press, demonstrated that impulse drying can provide significantly higher outgoing solids than double felted pressing at the same impulse. Installation in a fourth press position, results in cross directional compression strength increases of almost 30% over conventional pressing and drying. Sheet stickinq was a problem for both IPST ceramic roll and Beloit "C" roll surfaces. Felt durability was promising.

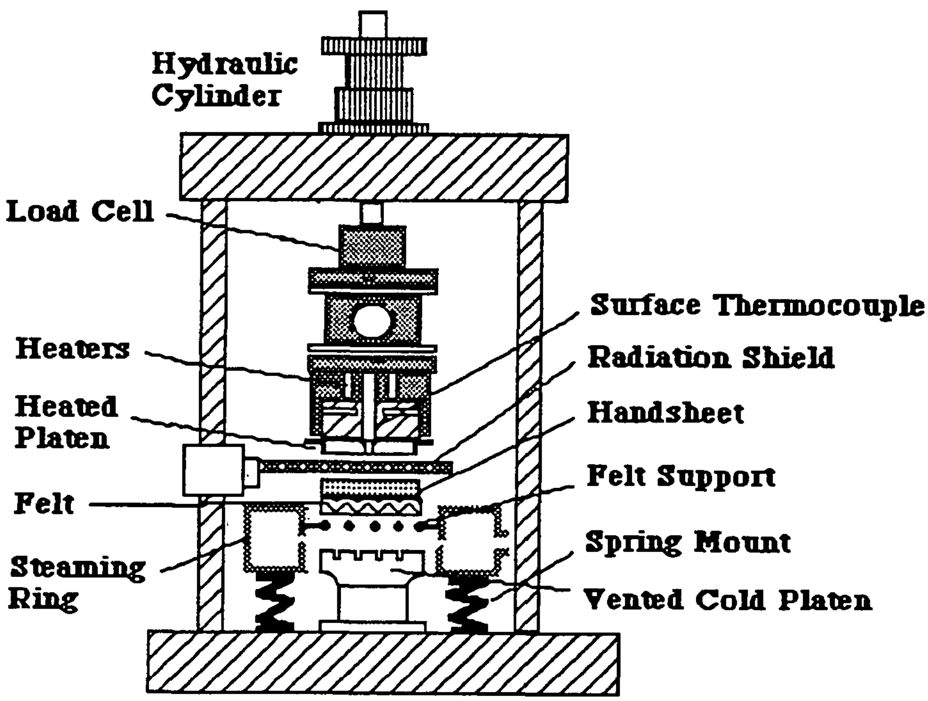


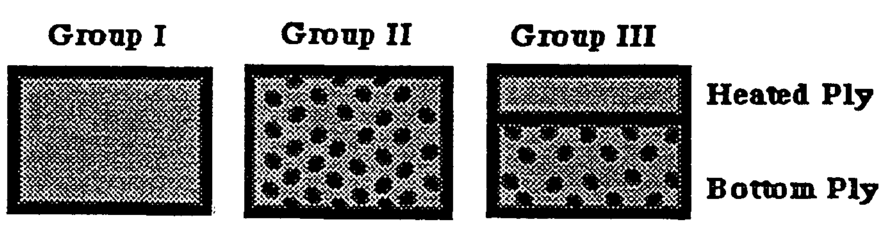
BELOIT PILOT SHOE PRESS X2
(Configured For Double Felted Pressing Or Impulse Drying)

IMPULSE DRYING OF MULTI-PLY SHEETS MADE WITH RECYCLED PULP

Laboratory-scale impulse drying experiments, funded by the Container Kraft Paper Group (CKPG) of the American Forest and Paper Association (AFPA), were conducted to identify important pulp substitution variables and quantify the benefit of impulse drying for multi-ply linerboard manufactured with recycled furnishes.

Impulse Drying Simulator



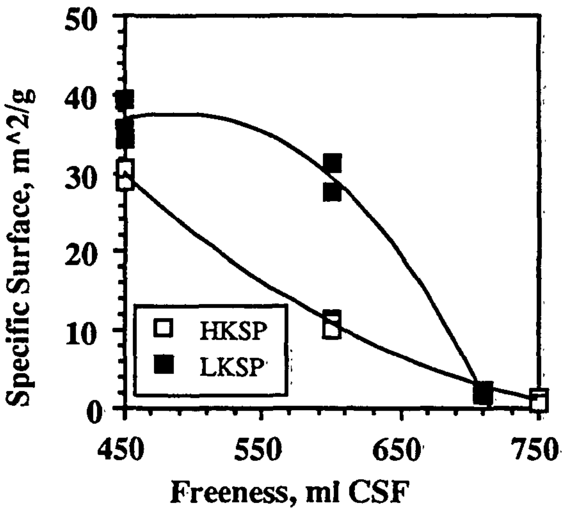


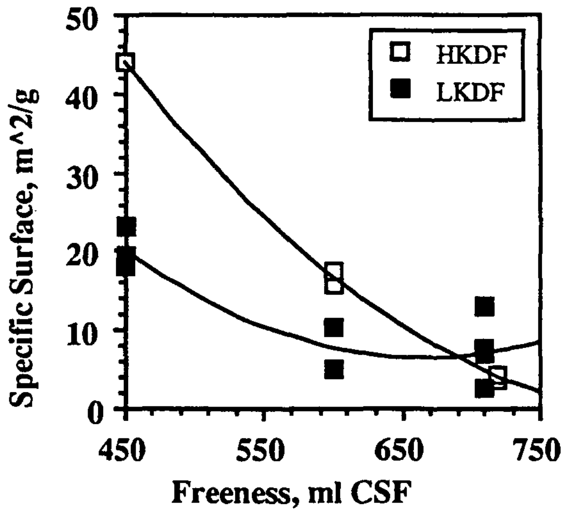
Schematic Of Sheet Structures

GROUP I EXPERIMENTS

Single-ply 42 lb liner, made from five minimally refined furnishes were impulse dried. The furnishes included; high and low Kappa number southern pine, high and low Kappa Douglas fir, and OCC.

Kappa number had little effect on impulse drying performance, while southern pine was found to have an advantage over Douglas fir since southern pine had lower fines concentration, at high freeness levels.

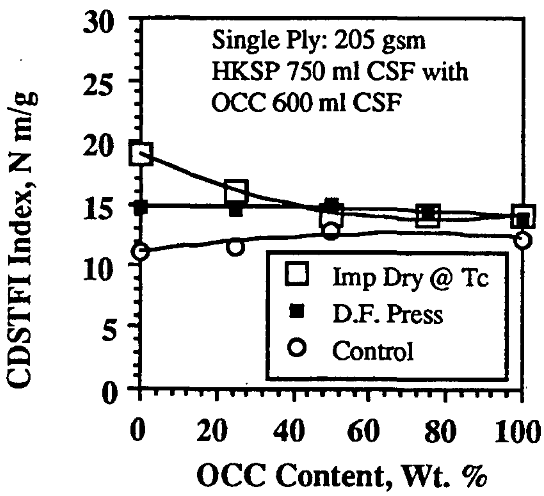


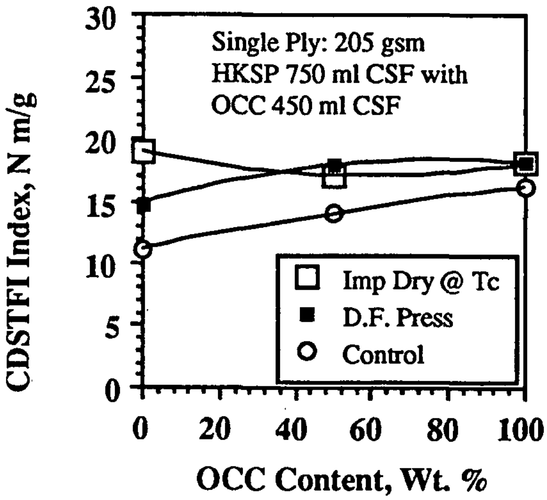


GROUP II EXPERIMENTS

These experiments were conducted to determine how much OCC could be blended with virgin Kraft and still be successfully impulse dried. Here the criteria for success was that the strength and dryness imparted by impulse drying be superior to that which could be achieved by conventional double felted pressing at the same impulse. Single-ply sheets were formed from blends of OCC refined to two different freenesses with a lightly refined virgin southern pine.

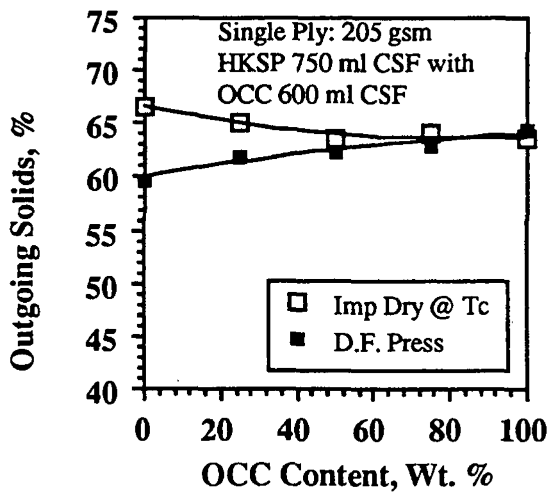
It was concluded that impulse drying had a the strength advantage at recycle concentrations of fifty percent or less.

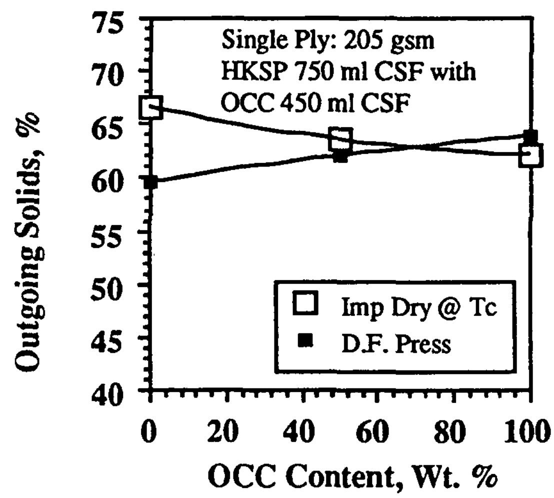




GROUP II EXPERIMENTS

Dryness advantages were observed for blends having recycle concentrations of seventy five percent or less.



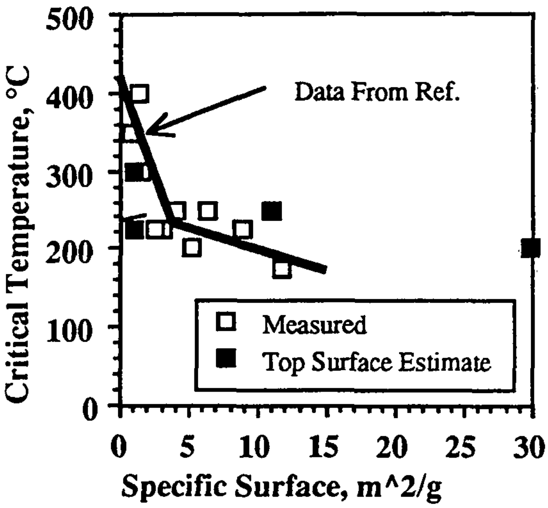


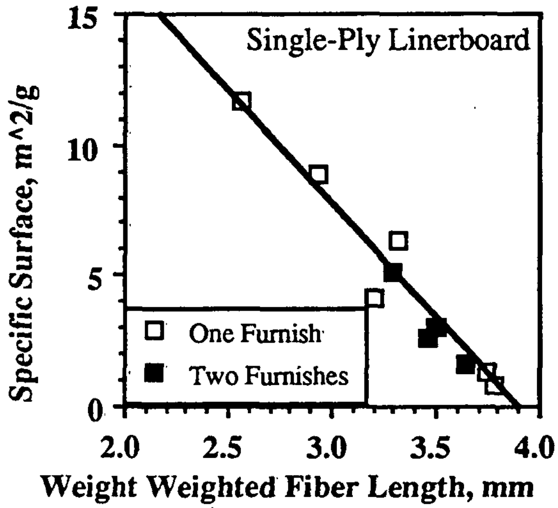
GROUP III EXPERIMENTS

In these experiments, two-ply sheets of various constructions were impulse dried to determine how the composition of the top and bottom layer influence optimum impulse drying operating conditions and resulting dryness and physical properties.

It was concluded that the composition of the part of the sheet in contact with the heated surface controls the critical impulse drying temperature.

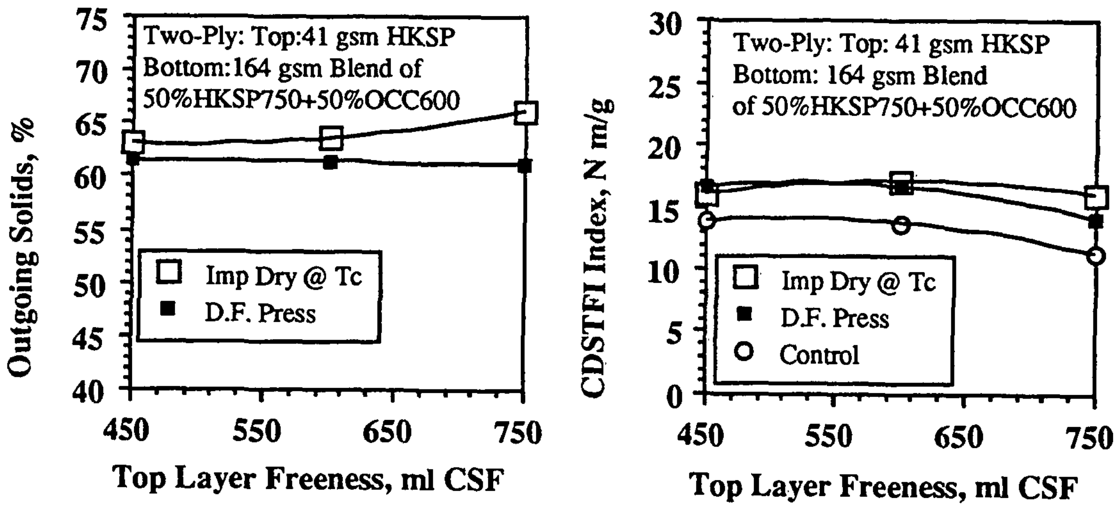
Hence critical temperature could be predicted from the hydrodynamic specific surface of the heated surface of the sheet, which in turn could be predicted from its fiber length distribution.





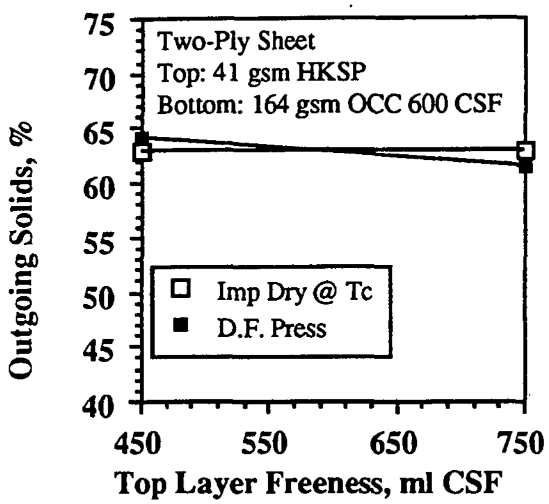
GROUP III EXPERIMENTS

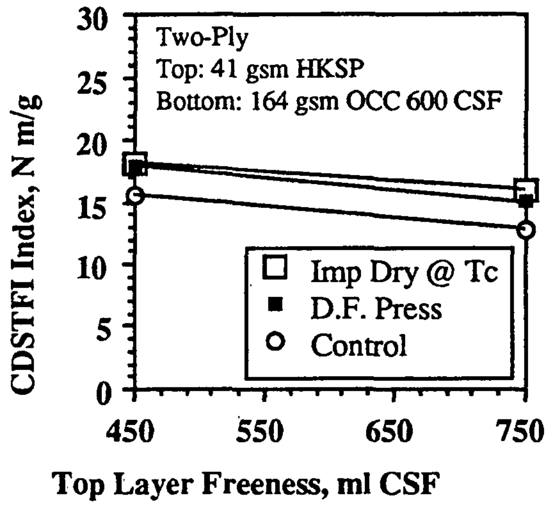
When the bottom sheet was composed of fifty percent virgin Kraft and fifty percent recycled fiber, superior impulse drying dryness and physical property development was observed for top sheet compositions having freeness of 450 ml CSF or more.



GROUP III EXPERIMENTS

Sheets constructed with a bottom sheet of recycled fiber and a top sheet of virgin Kraft showed enhanced dryness and strength as long as the heated surface of the sheet had a freeness of 600 ml CSF or more.

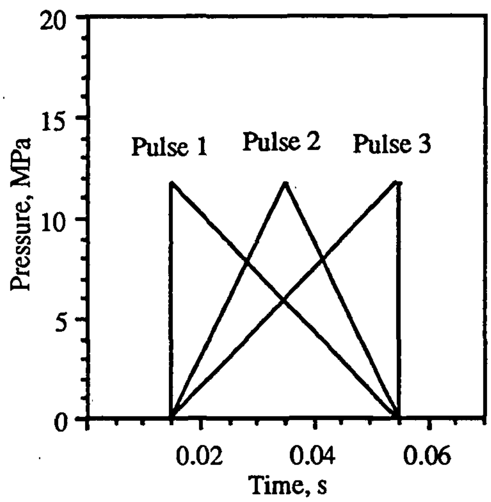




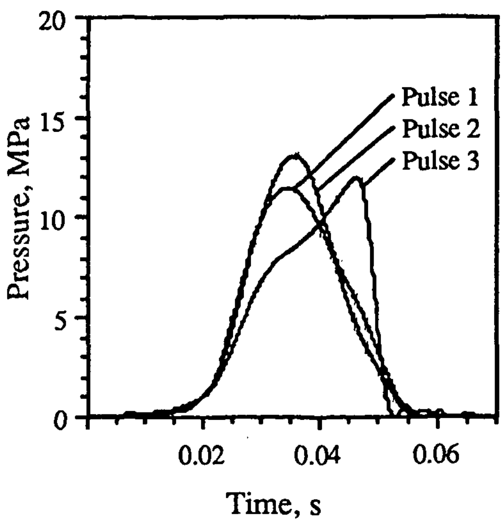
THE EFFECT OF PRESSURE PULSE SHAPE

Dues funded lab-scale experiments were performed with a ceramic coated platen and with both low specific surface, lightly refined, southern pine Kraft and high specific surface, heavily refined OCC.

It was determined that pressure pulse shape is an important operating variable that may be used to adjust the shape of the heat flux curve.



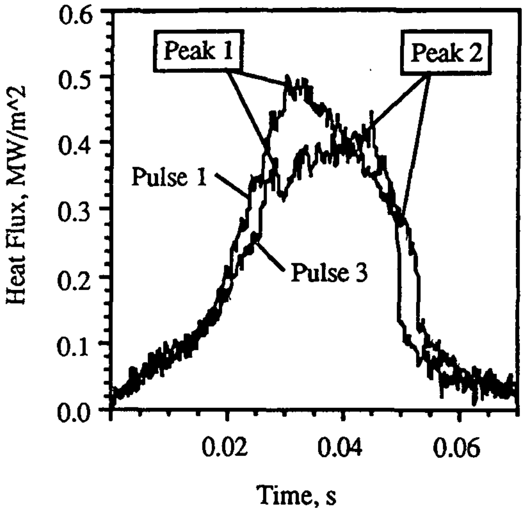
Pulse shapes from signal generator



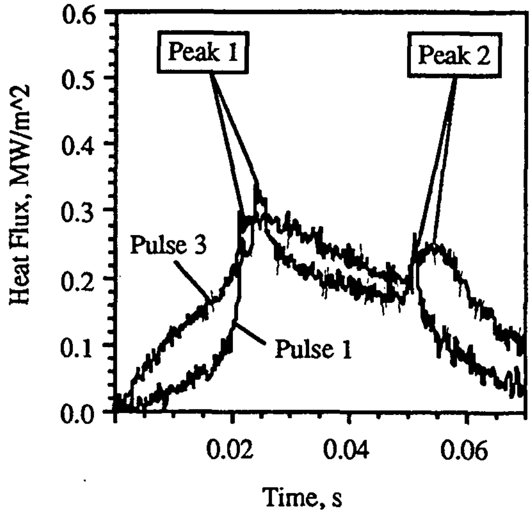
Pulse shapes recorded by transducer

$$\textbf{Shape Factor} = \frac{\textbf{Time of Pressure Peak}}{\textbf{Nip Residence Time}}$$

THE EFFECT OF PRESSURE PULSE SHAPE



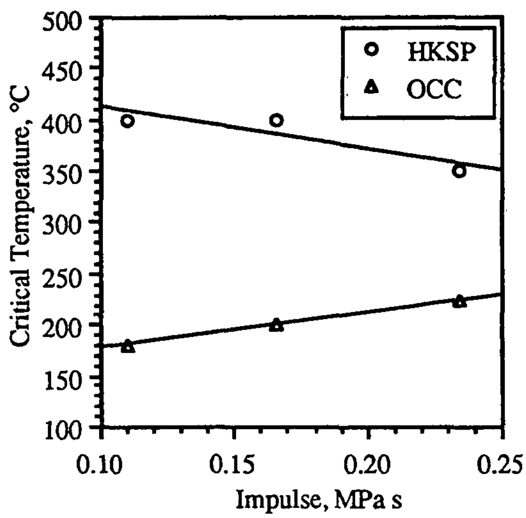
HKSP at 0.23 MPa·s and 300° C.



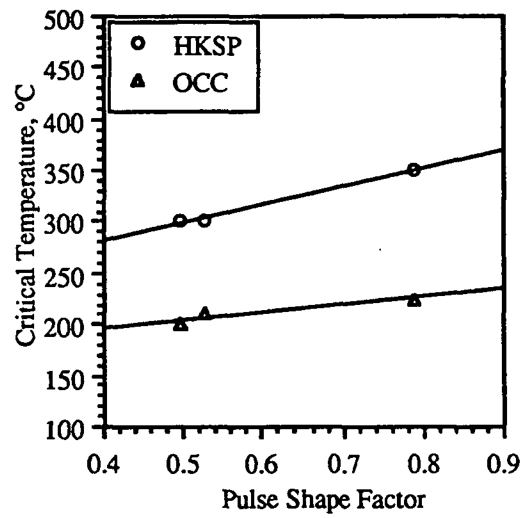
OCC at 0.23 MPa·s and 200° C.

THE EFFECT OF PRESSURE PULSE SHAPE

Critical temperature depends on impulse and pulse shape factor as well as on hydrodynamic specific surface and the thermal properties of the impulse drying surface.



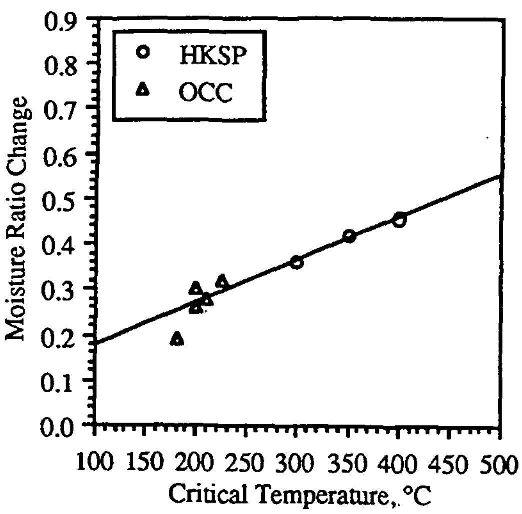
Critical temperature for pulse shape 3



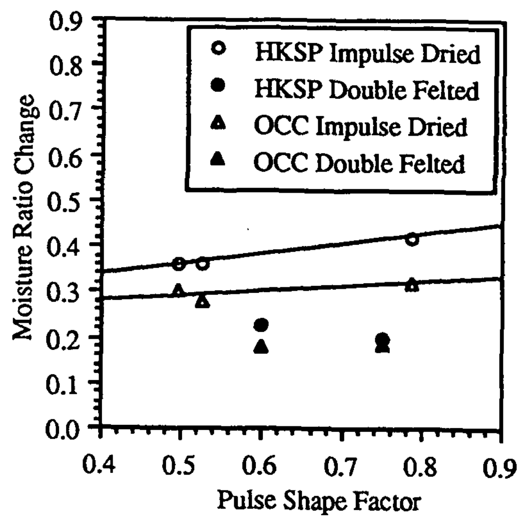
Critical temperature at 0.23 MPa·s.

THE EFFECT OF PRESSURE PULSE SHAPE

As higher critical temperatures result in improved water removal, operating at high pulse shape factor results in improved water removal.



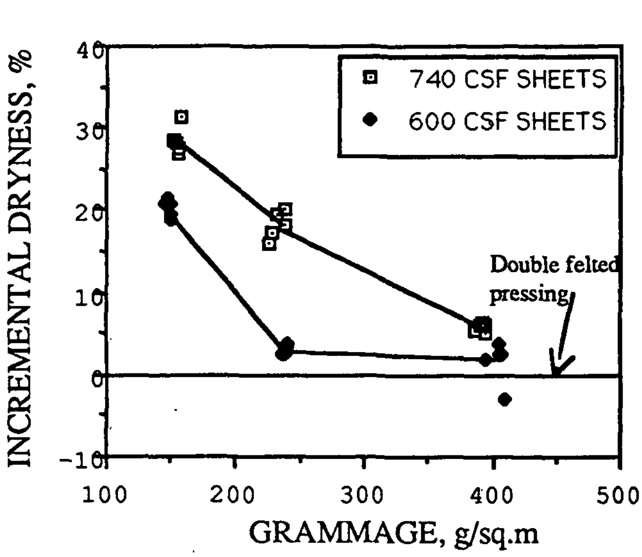
MRC vs. critical temperature.

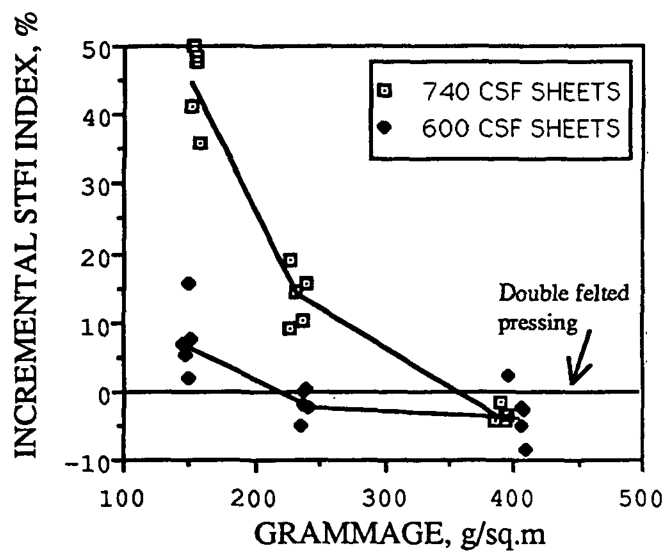


MRC at 0.23 MPa·s

EXTEND THE RANGE OF BASIS WEIGHTS

Student research has shown that the benefits of impulse drying as compared to double felted pressing should be expected to be realized for basis weights approaching 350 gsm. The work also showed that the "break even" basis weight depended on the specific surface of the furnish.





GOALS FOR FY 93-94

The ultimate objective of this program is the commercialization of impulse drying technology for heavy weight grades of paper such as linerboard. The work described here will be performed with the cooperation of the Beloit Corporation and the Container Kraft Paper Group of the American Paper Institute. The work will focus on six major objectives.

1) To resolve sheets sticking difficulties observed in earlier batch-pilot extended-nip shoe press experiments.

2) To demonstrate and optimize impulse drying of multi-ply / recycle containing paper on the batch-pilot extended-nip shoe press.

3) To develop a numerical model of a controlled-crown impulse drying press roll to explore design parameters that allow high internal oil temperatures for maximum roll heating efficiency.

4) To verify the numerical model in bench scale experiments.

5) To design (for implementation in 1994) a high speed test stand equipped with induction heating system to monitor stresses within the ceramic coating and to document the long term durability of the ceramic coatings during simulated impulse drying.

6) To determine the interdependency of the "thermal mass."of the heated press roll surface, the pressure pulse shape and press impulse on impulse drying performance. Optimize the roll surface for; impulse drying performance, energy efficency and mechanical strength. This work will be undertaken as a student project in 1993.

MARCH 1993 IPST/BELOIT PILOT EXPERIMENTAL PLAN

Objectives Of Experiments

- ❑ Impulse dry using Beloit A and Ceramic rolls with de ionized felt water document any sheet sticking
- ❑ Compare impulse drying to double felted pressing
- ❑ Determine if high press loads are justified
- ❑ Compare performance of two roll coatings for furnishes having wide range of specific surface
- ❑ Demonstrate impulse drying of recycled and two-ply liner
- ❑ Compare impulse drying of Southern pine & Douglas fir
- ❑ Determine the preferred felt and pressure pulse shape.

MARCH 1993 IPST/BELOIT PILOT EXPERIMENTAL PLAN

Experimental Matrix Of Conditions For Each Furnish

Machine	X2 Shoe Press																							
Configuration	Double Felted								Impulse Drying															
Felt Type	B				Special				B								Special							
Pivot Position	0		+2		0		+2		0				+2				0				+2			
Roll Cover	Not Applicable								A		Cer		A		Cer		A		Cer		A		Cer	
Load	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L
No. Of Temps.	Not Applicable								6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
No. Of Repeats	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Speed: 1200 fpm
Load, L = 6000 pli, H = 8500 pli
Roll Surface Temperatures: 100°C, 150°C, 200°C, 250°C, 300°C, 350°C.
All Sheets To Have Ingoing Solids Of 52%
All Sheets To Be Steamed Prior To Impulse Drying Or Double Felted Pressing Using Same Apparatus.

MARCH 1993 IPST/BELOIT PILOT EXPERIMENTAL PLAN

<u>Furnish Cases</u>

	Composition Of Top Ply			Composition Of Bottom Ply		
Case	**Pulp Type**	**Freeness, ml**	**Weight %**	**Pulp Type**	**Freeness, ml**	**Weight %**
WF1			0	HKSP	740	100
WF2			0	HKSP	600	100
WF3			0	HKDF	720	100
FD5			0	OCC	450	100
FD6	HKSP	740	20	HKSP OCC	740 600	40 40
FD7	HKDF	720	20	HKDF OCC	720 600	40 40

MARCH 1993 IPST/BELOIT PILOT EXPERIMENT

Preliminary Results

- ❑ Beloit A and Ceramic rolls were operated without sheet sticking at temperatures above 150°C with de ionized felt water. The Beloit A roll also did not stick when hard felt water was used. The Ceramic roll is suseptable to chipping under shear, the Beloit A roll did not chip.
- ❑ Impulse drying was superior to double felted pressing in press dryness. Physical testing is in progress.
- ❑ Critical temperatures appeared to agree with lab-scale experiments
- ❑ Impulse drying of recycled and two-ply liner was demonstrated
- ❑ Douglas fir as well as Southern pine could be impulse dried

COMMERCIALIZATION

Research Consortium Is Being Formed

Proposed Organizational Structure